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A review of solar drying technologies

S. VijayaVenkataRaman[a], S. Iniyan[b,*], Ranko Goic[c]

[a] Department of Mechanical Engineering, College of Engineering, Anna University, Chennai, India
[b] Institute for Energy Studies, Anna University, Chennai, Tamil Nadu 600025, India
[c] Department of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia

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ABSTRACT

Agricultural products such as coffee, tobacco, tea, fruit, cocoa beans, rice, nuts, and timber generally require drying through a consistent application of relatively low heat. Traditionally, crop drying has been accomplished by burning wood and fossil fuels in ovens or open air drying under screened sunlight. These methods, however, have their shortcomings. The former is expensive and damages the environment and the latter is susceptible to the variety and unpredictability of the weather. Solar crop drying is a happy medium between these two methods and it dries crops with more efficiency, uniformity, and less expense. A solar crop drying system does not solely depend on solar energy to function; it combines fuel burning with the energy of the sun, thus reducing fossil fuel consumption. In this paper, the status of solar drying technologies in developing countries is presented. The various designs of solar dryers, its types and performance analysis are reviewed. Special attention is given to the solar drying technologies that facilitate drying of crops in off-sunshine hours. The solar dryers specifically designed or tested using specific crops like the vegetable dryer, fruit dryer, grain dryer, grape dryer, and so on are also reviewed with details about the specifications and the results. In short, the state of art technologies and development of solar dryers are presented in this paper.

Contents

* Corresponding author. Tel.: +91 44 22531070; fax: +91 44 22353637.
E-mail address: iniyan777@hotmail.com (S. Iniyan).

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1. Introduction

According to investigations around 15% of the world population today is undernourished. The increase in world population will strengthen the yet existing population–food imbalance. Besides increasing food supply and limiting population growth, drastically reducing the food losses which occur throughout food production, harvest, post-harvest, and marketing seems to be a viable option. The reduction of food losses is particularly a problem for small farmers in developing countries who produce more than 80% of the food. Solar drying is in practice since time immemorial for preservation of food and agriculture crops. This was done particularly by open sun drying under the open sky. Since traditional sun drying is a relatively slow process, considerable losses can occur. In addition, a reduction in the product quality takes place due to insect infestation, enzymatic reactions, microorganism growth, and mycotoxin development. This process has several disadvantages like spoilage of product due to adverse climatic condition like rain, wind, moist, and dust, loss of material due to birds and animals, deterioration of the material by decomposition, insect infestation and fungal growth. Also the process is highly labor intensive, time consuming, and requires large area. With cultural and industrial development, artificial mechanical drying came into practice. This process is highly energy intensive and expensive, which ultimately increases product cost. Thus solar drying is the best alternative as a solution of all the drawbacks of natural drying and artificial mechanical drying (Figs. 1–10).

Solar dryers used in agriculture for food and crop drying are used for industrial drying processes. They can be proved to be a very useful device from the energy conservation point of view. It not only saves energy but also saves a lot of time, occupies less area, improves quality of the product, makes the process more efficient, and also protects the environment. Solar dryers circumvent some of the major disadvantages of classical drying. Solar drying can be used for the entire drying process or for supplementing artificial drying systems, thus reducing the total amount of fuel energy required.

Three key barriers to increase use of solar crop drying are:

- the lack of awareness of the cost-effectiveness of solar drying systems.
- the lack of good technical information.
- the lack of good local practical experience.

The objective is to address the three barriers above by providing technical and commercial information and experience gained from the design, construction and operation of full-scale, commercially viable solar drying systems for a variety of crops and a number of geographical regions, where solar energy is expected to have the greatest potential. It is surprising that a process used as commonly as solar drying has received so little technical development. With the enormous tonnage of materials being processed by this method, greater effort in its development and improvement would seem in order. It is not unreasonable to believe that annual saving in the millions of dollars might be realized through lowering the costs of drying, improving the quality of the products, and reducing losses by spoilage, deterioration, transport delays, and other factors [1]. Solar drying can be an effective means of food preservation since the product is completely protected during drying against rain, dust, insects and animals [2]. Significant developments of the past decade in the area of solar crop drying were reviewed by Muhlbauer, stating the fact that solar energy is considered more applicable to low-temperature in-storage drying systems and it has gained more importance in the last decade for drying grain and hay [3]. Purohit et al. developed a simple framework to facilitate a comparison of the financial feasibility of solar drying as against open sun drying, having presented the results of some exemplifying calculations and a brief discussion about the same [4]. Ekechukwu presented a comprehensive review of the fundamental principles and theories governing the drying process, along with basic definitions [5]. A comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically-realised designs of solar energy drying systems was presented by Ekechukwu and Norton. A sys-

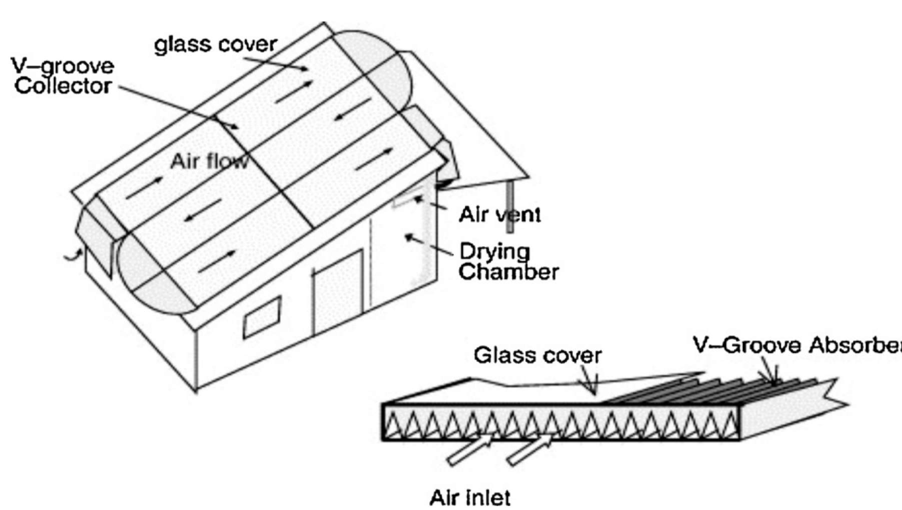

Fig. 1. Solar drying system with V-groove solar collector for drying medicinal herbs developed by Othman et al. [41].

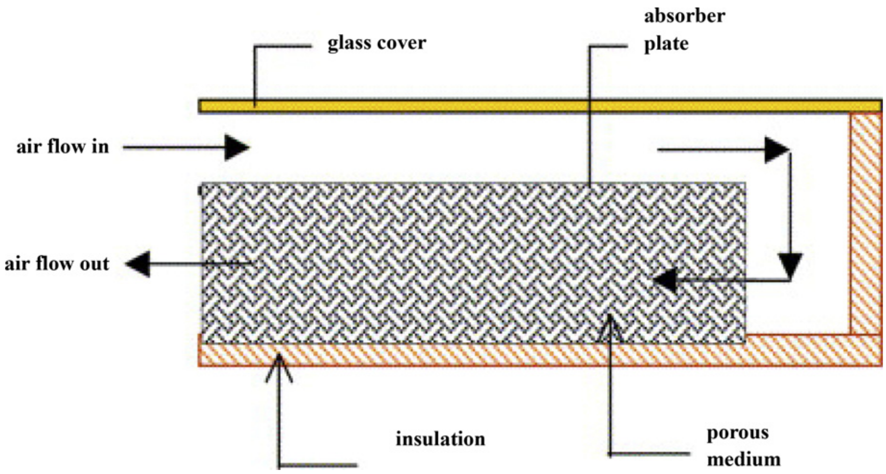

Fig. 2. The schematic of a double-pass solar collector with porous media for solar drying system developed by Othman et al. [41].

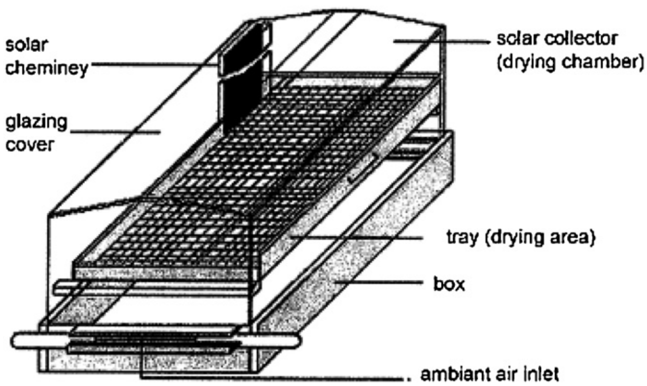

Fig. 3. Direct solar dryer using a thermal circulator developed by Gbaha et al. [55].

tematic approach for the classification of solar energy dryers were also evolved, identifying two generic groups, namely, passive or natural circulation solar energy dryers and active or forced convection [6]. A review of the various designs and the performance evaluation technique of flat-plate solar energy air heating collectors for low temperature (temperature elevations between 10 °C and 35 °C above ambient) solar energy crop drying applications were presented by Ekechukwu and Norton. The appropriateness of each design and the component materials selection guidelines were also highlighted [7]. Fudholi et al. reviewed various types of solar dryers with respect to the product being dried, technical and economical aspects, considering the fact that the solar dryers can be classified basically into four types namely Direct solar dryers, Indirect solar dryers, Mixed-mode solar dryers, and Hybrid solar dryers [8]. Low cost drying technologies suitable for rural farming areas were presented by Chua and Chou. A brief introduction on each of the drying technology considered namely fluidized bed, spouted bed, infrared, solar, simple convective, and desiccant drying were presented followed by some technical details on their working operations [9]. Sharma et al. gave a preliminary economic analysis for an indirect type solar fruit and vegetable dryer and the analysis stressed that the most significant economic parameters in the lifecycle costing of the system were the payback period and internal rate of return, in addition to other important and influential parameters, namely, initial investment, fuel price, interest on fuel price, etc. [10].

2. Solar drying in various countries

The effects of prospective use of direct solar energy for power production, saline water distillation, refrigeration and air conditioning, water heating, crop drying, etc. on the prosperity of developing countries were discussed by Saif-Ul-Rehman, presenting in detail the analysis of the difficulties in the way of solar energy utilization due to the economic limitations as compared with conventional fuels [11]. The traditional method of solar drying in the Asia-Pacific region is by open air drying where the product to be dried is exposed directly to the sun. Having visited a number of countries, Ong studied the numerous designs available for solar drying in this region. Three types of solar dryers considered by Ong

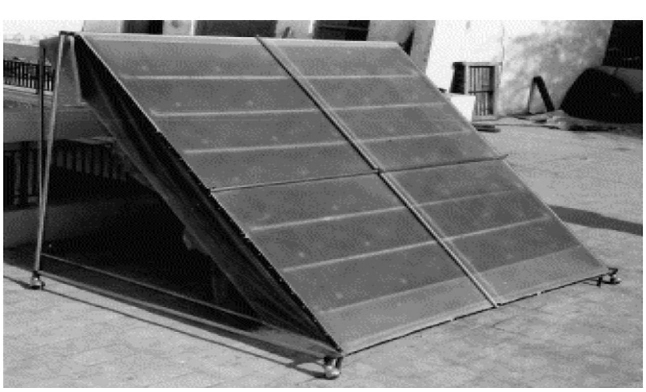

Fig. 4. PAU portable form solar dryer developed by Singh et al. [67].

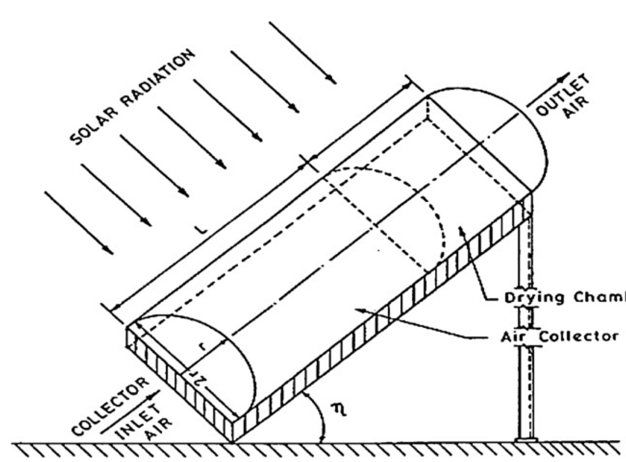

Fig. 5. Schematic of semi-cylindrical solar tunnel drying system developed by Garg and Kumar [74].

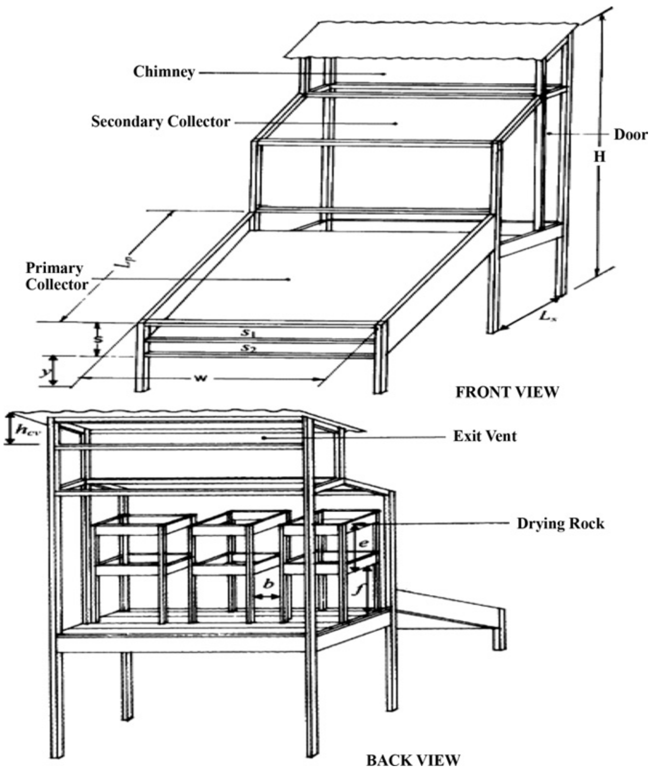

Fig. 6. Schematic views of the mixed-mode natural convection solar crop dryer developed by Forson et al. [81].

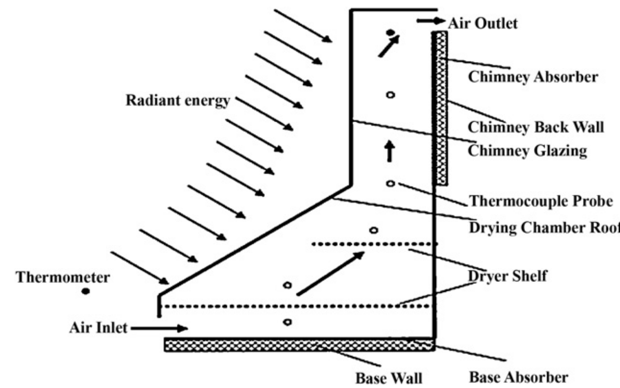

Fig. 7. Functional architecture of the chimney-dependent direct-mode solar crop dryer developed by Afriyie et al. [83].

as having the best potential for development in Asia-Pacific region, namely, natural convection cabinet type solar dryer, the forced convection indirect solar dryer and the greenhouse type solar dryer, were discussed in detail [12]. Vecchia et al. described the methodology followed and the main results of a study, which was limited to thermal forms of energy consumptions, performed under the contract for the Commission of the European Communities. An assessment on the possibilities of penetration of solar technologies in European countries in the sectors, namely, rural houses (space heating and hot water production), shelter heating, hot water production for animal husbandry, greenhouse heating and crop drying were also given [13]. The research results and practical experiments obtained in the past 20 years in Europe showed that the use of flat-plate solar collectors in the drying processes has a large potential and enables reduction of fuel consumption. Wisniewski felt that the stimulators of the market development of solar dryers are not only the direct economic advantages but also the social needs defined at the local level, while briefing about the market development of the solar crops drying technologies in Poland and Europe [14]. Arinze et al. realized the need for application of artificial drying techniques to reduce the risks of crop spoilage in field drying of forage crops in the hay-making process in North America, as an important management tool in livestock production in the selection of appropriate drying systems for forage crops. They therefore developed a computer program to simulate the solar heated and natural air hay drying systems and validated it by comparing the model predicted results with the experimental data obtained from a batch dryer and field drying for fresh alfalfa crops. The effects of insolation, air flow rate, air temperature and humidity, initial moisture content, dry matter density and stack height of hay on drying times to 18% safe storage moisture content were investigated and it was found that time and fan power savings of about 30% and 45% were achieved by using the solar heated air drying system as against natural air system in June and August respectively for Saskatoon [15]. Kumar and Kandpal made an attempt to estimate the potential of solar crop drying for some selected cash crops in India. The potential of net fossil CO_2 emissions mitigation due to the amounts of different fuels that would be saved by solar drying in India were also estimated along with the unit cost of CO_2 emissions mitigation [16]. Solar air heaters of many types were developed in India and their performances were studied in detail by Bansal. The potential of

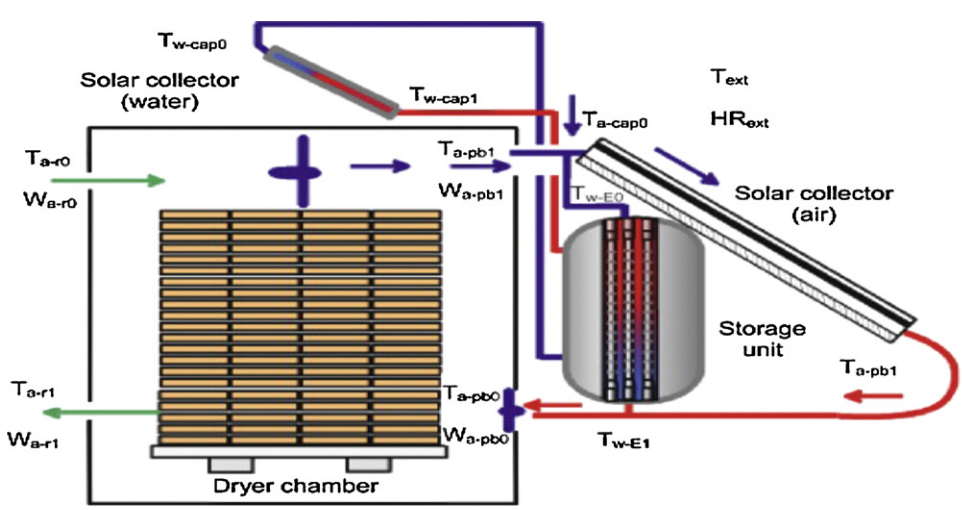

Fig. 8. Solar kiln dryer with energy storage developed by Luna et al. [96].

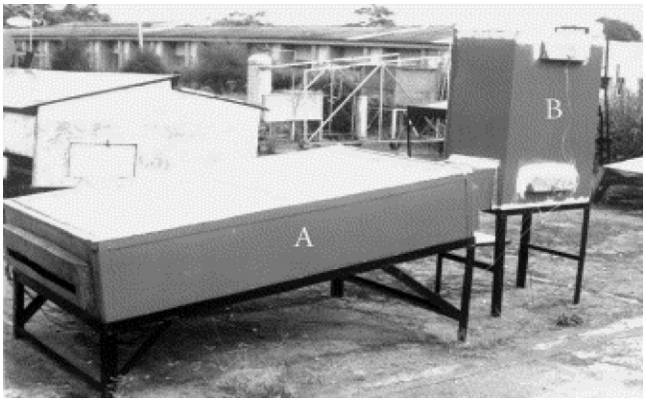

Fig. 9. Photograph of the air heating system consisting a collector assembly with energy storage and air-heating subsystems developed by Enibe [98].

solar heaters for the drying process of a few cash crops were also assessed in detail [17]. The application of solar drying systems was introduced in Nepal for the preservation of food and income generating activities. A nationwide survey revealed that three types of solar drying systems were in common use, namely, cabinet type for domestic use, racks type for commercial and tunnel type for industrial purposes. Modifications in design, construction materials and capacity were done by Joshi et al. to match the local needs and improve the performance of these three types of dryers [18]. The technical and financial performance of an existing solar crop dryer at Khao-Kor, Thailand was evaluated by Tshewang Lhendup, for possible replication in Bhutan. Chilli and beef were selected as products to be dried as they were an integral part of Bhutanese cooking. The solar dryer system was found cheaper to dry beef while an electric heating system was found cheaper to dry chilli [19]. Research and development work in solar drying conducted in Thailand in the past 15 years was reviewed by Somchart Soponronnarit and the technical and economic results indicated that solar drying for some crops such as paddy, multiple crops and fruit is feasible [20]. Longan is one of the most widely grown fruits in Northern Thailand, where a significant amount of the annual harvest is commercially dried and exported as a commodity. Liquefied petroleum gas is generally used as the energy source for heating the drying air. Roman et al. used a simulation program for a flat-plate solar air heater to estimate the potential to preheat the drying air given the conditions of several longan drying facilities. Results showed that solar collectors can replace up to 19.6% of the thermal energy demand during the drying season and the annual monetary savings can reach up to THB 56,000 [21]. Oztek et al. investigated the present status of agricultural crop drying practices in Turkey, giving a broad perspective on the emphasis of drying on market value, annual production and export values of some commercially important crops [22]. Salihoglu et al. investigated to find an economical solution to the sludge management problem in Bursa city of Turkey and recommended limited liming and solar drying as an alternative to only-liming the mechanically dewatered sludge. It was found that, if the limited liming and solar drying method was applied after mechanical dewatering instead of only-liming method, the total amount of the sludge to be disposed would be reduced by approximately 40%, which in turn would lead to a reduction in the transportation, handling and landfilling costs [23]. Solar thermal devices have been used in the West Indies islands for over a century. Traditionally, crops such as rice or cocoa have been dried in the sun on drying floors. In the last 25 years solar water heaters have become commercially available and over 30,000 are now in use in Barbados and about 2000 in Jamaica. Solar stills and solar crop dryers have also been deployed and solar collectors have been used to power solar cookers and adsorption chillers [24]. The design and operation of solar agricultural dryers which have been used to dry a variety of crops all over the Caribbean region were described by Headley [25]. A small solar crop dryer, consisting of a drying unit, thermal storage and solar collector, was designed for the climatic conditions of Papua New Guinea, and was constructed and tested at the Energy Research site of the University of Papua New Guinea, by Lawrence et al. Detailed experimental studies were carried out for drying of tapioca, as well as the testing of the drying unit with and without thermal storage [26]. A comprehensive study for the utilization potential of solar drying in Saudi Arabia was accomplished by Zahed et al. Data pertinent to solar insolation and important for the country's agricultural products (e.g. wheat, dates) were presented, along with a discussion of various solar drying systems of crops. Four of these systems were proposed having features such as use of concurrent drying technique, use of heat pipes, thermal storage and boosters and a computer simulation study for a proposed system of concurrent drying of grains showed over 35% energy saving when heating is partially delivered by the solar collector component of the system [27]. Cheapok and Pornnareay gave a description of the efforts made under the regional research and

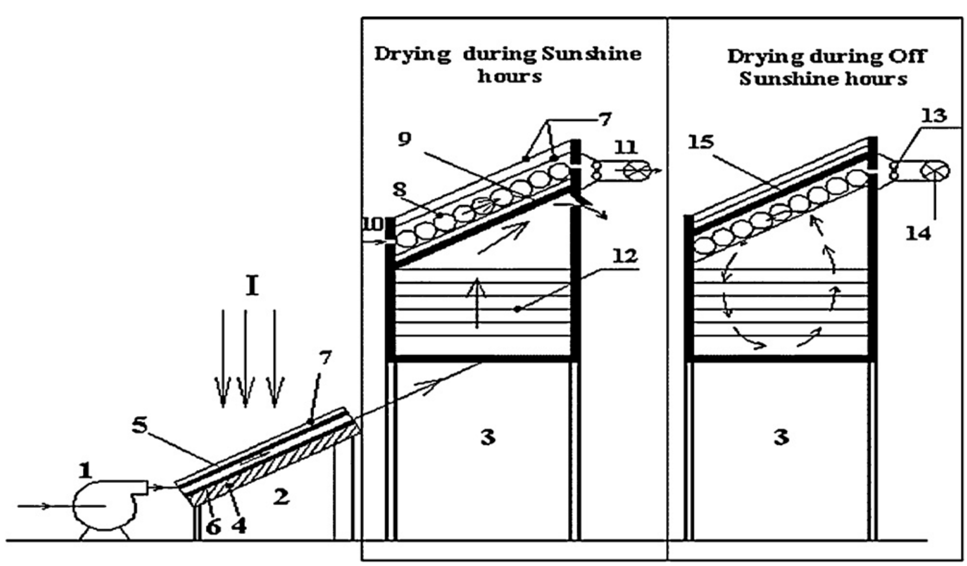

Fig. 10. Schematic of the desiccant integrated solar dryer developed by Shanmugam and Natarajan [102].

dissemination program, which supported the development of solar dryers in Cambodia, to design, develop and test two types of solar dryers (cabinet dryer and chimney dryer) that match the needs and requirements in Cambodia. Experimental trials on these dryers gave satisfactory results and the results showed that they are suitable for local dissemination [28]. Current and projected food preservation and solar crop dryer availability figures were given by Ben Mabrouk and Belghith, along with potential renewable energy sources in Tunisia [29]. Roman presented a concise survey about solar crop drying with explanations about the traditional drying, industrial drying and the techniques of drying in general. The solar drying in Chile and its practical advantages were then presented in detail [30].

3. Design, development and performance evaluation of various types of dryers

Sharma et al. presented a comprehensive review of the various designs, details of construction and operational principles of solar energy drying systems. A systematic approach for the classification of solar energy dryers was also evolved [31]. Solar drying systems of different designs and the testing procedures for solar dryers was reviewed by Sodha and Chandra [32]. Augustus Leon et al. presented a detailed review of parameters generally used in testing and evaluation of different types of solar food dryers, highlighted the inadequacies of the parameters generally reported and suggested additional parameters. Based on the review, a procedure was proposed, giving the methodology, test conditions and a sample evaluation sheet, which would assist in an unambiguous evaluation of solar dryer performance and facilitate comparing of different solar food dryers [33]. Ramana Murthy reviewed various aspects of solar dryers applied to drying of food products at small scale and the popular types of dryers found in the Asia-Pacific region and new types of dryers with improved technologies were discussed. The performance evaluation of the dryer was discussed in detail and it was found that there is a shorter way of estimating the performance of a dryer [34]. Arata and Sharma investigated the most appropriate cost effective food preservation technology suitable for implementation with limited financial resources, meaning that the simple designs discussed in the paper can be fabricated using simple tools and relatively cheap and locally available materials by small scale industries [35]. Sharma et al. presented an experimental investigation of three different types of solar dryers based on the principle of natural as well as forced convection and efforts were made to select the most appropriate design to be used on a household, farm or on an industrial scale [36]. Various experimental techniques were described by Chandra and Sodha to allow the net thermal output of an irradiated solar air heater array to be reproduced indoors. The effect of air leaks was incorporated in to the performance equations. Other well-known testing procedures were also described. A method for generating design data for solar air heaters was described [37]. Different types of active air type solar collectors were examined by Henriksson and Gustafsson, for two main applications namely drying of agricultural crops and heating of animal houses. It was found that there are benefits if the solar collector is integrated in to the building and the types of dryers which have been tested have the potential to compete economically with oil as a heat source [38]. Six different types of natural circulation air heating solar collectors (Model-1: single plastic glazing, black painted hardboard absorber and front-pass; Model-2: single plastic glazing, black painted flat-plate absorber and front-pass; Model-3: single plastic glazing, black painted zigzag plate absorber and front-pass; Model-4: single plastic glazing, black painted flat-plate absorber and back-pass; Model-5: single plastic glazing, black painted zigzag plate absorber and back-pass; Model-6: double plastic glazing, black painted flat-plate absorber and back-pass) were designed, constructed and analyzed for their performance by Turhan Koyuncu. It was reported from the results of the investigation that the performances of Model-1, Model-2, Model-3, Model-4, Model-5, and Model-6 were 42.11%, 45.88%, 44.23%, 39.76%, 39.05%, and 36.94% respectively, and the performance of the most efficient collector (Model-2) is approximately 9% more than the least efficient one (Model-6) [39]. A non-mechanical solar dryer based on convective heat and mass transfer, with energy storage, constructed from materials available locally, was constructed and tested by Ayensu and Asiedu Bondzie to investigate the drying characteristics of various tropical products [40]. Othman et al. developed four solar assisted drying systems namely the V-groove solar collector, the double-pass solar collector with integrated storage system, the solar assisted dehumidification system for medicinal herbs and the photovoltaic thermal (PVT) collector system, which have the advantages of heat storage, auxiliary energy source, integrated structure control system and can be use for a wide range of agricultural produce [41]. Suspended-plate solar air heaters were installed on farms in Tennessee to supply heat for grain and crop drying. The heaters were telemetrically monitored by Womac et al. to determine thermal performance and to allow subsequent analyses of economic feasibility. Results of the thermal analysis revealed that solar air heaters will successfully provide a suitable air temperature rise during most crop drying conditions [42]. A simple solar collector cum crop drying system was described by Garg et al., with the categorical objectives of identifying a suitable medium capacity solar drying system and to study analytically and experimentally the performance characteristics of this newly fabricated solar drying system [43]. Tiris et al. dealt with the construction and performance of a solar powered drying system consisting of a solar air heater and a drying chamber. The thermal efficiencies of both the solar air heater and the drying section as a function of typical physical parameters and the experimental results for different food products at different air flow rates were discussed. The results indicated that the present drying system has thermal efficiencies between 0.3 and 0.8 during drying experiments and that the higher flow rates increase the overall drying performance and efficiency [44]. The energy balance equations for a passive solar crop dryer with shallow bed, including the effect of a reflector placed over the wall of the chimney were written in terms of design and climatic parameters by Tiwari et al. Taking into account the effects of thermal storage and the crop, analytical expressions for the outlet air temperature of the collector and the temperature of the storage material and the crop were derived and on the basis of the analytical results, it was observed that the drying time is significantly reduced due to the increase in thermal energy on the collector by the reflector [45]. Pitt considered the relation between pan evaporation and drying of crops in the field, after cutting, and the sources of variability in that relationship. Pan evaporation is considered as a climatic measurement that integrates the effects of temperature, wind speed, humidity, and solar intensity on drying rate. Crop drying was modeled as a stochastic diffusion of water molecules out of the crop surfaces. The model predicted the expected moisture ratio to be an exponentially decaying function of accumulated pan evaporation. Results of field experiments showed that the drying rate of any given forage sample can be accurately characterized by the drying constant measured in relation to pan evaporation [46]. The main application for solar energy in southern Mediterranean countries in agriculture is the drying of agricultural crops. Chemkhi et al. presented a study concerning thermal behavior of a solar air heater as a source of energy for drying agricultural products, with the purpose of calculating the fluid outlet temperature, the output energy used and thermal efficiency as a function of ambient temperature, incident solar radiation, wind speed, and air mass flow rate [47]. The knowledge of moisture

diffusion, D_{eff} and convective mass transfer, h_m coefficients during drying of food product is necessary in modeling and optimization of solar dryers. Tripathy and Kumar proposed a methodology for the determination of these coefficients using variable drying parameters (lag factor, k_0 and drying coefficient, k). Mixed-mode solar dryer with potato cylinders and slices was used to obtain variable (temperature dependent) k_0 and k from drying kinetics. Results of investigation indicated the increasing trend of D_{eff} and h_m with temperature and their values were found to be higher for cylinders compared to slices. Temperature rise from 33 °C to 48 °C for cylinders during drying resulted in the increase of 85.6% and 159% of D_{eff} and h_m, respectively, whereas these figures were 72% and 89% for slices [48]. An attempt was made by Anwar and Tiwari to evaluate the convective heat transfer coefficient operating in crop drying in open sun drying conditions (natural convection). Values of the constants, C and n were obtained by linear regression analysis from experimental data obtained for six crops, namely green chillies, green peas, Kabuli channa, onion, potato, and cauliflower. Analysis was also performed for Kabuli channa under natural cooling conditions. Based on the values of C and n, convective heat transfer coefficients for these crops were determined [49]. A simulation study was conducted by Anwar and Tiwari to determine the convective heat transfer coefficients of six crops, namely, green chillies, green peas, white gram, onion, potato, and cauliflower under forced convection drying. Data obtained from experimentation under open and closed simulated conditions were used to determine values of the coefficients C and n and consequently, the convective heat transfer coefficient [50].

3.1. Natural convection solar dryers

Sharma et al. investigated the means for food preservation using processes suitable for implementation in rural areas, where energy resources are scarce and fabricated different types of natural convection solar dryers, bearing in mind the low cost of capital investment and utilization possibilities, which is mainly agricultural drying. They presented the performance of the various types of solar dryers, along with a preliminary heat transfer analysis [51]. A transient analytical model was presented by Jain to study the new concept of a solar crop dryer having reversed absorber plate type collector and thermal storage with natural airflow. The parametric study involved the effect of width of airflow channel and height of packed bed on the crop temperature and it was observed that the crop moisture content and drying rate decreases with the drying time of the day [52]. A direct-type natural convection solar dryer and a simple biomass burner were combined by Benon Bena and Fuller to demonstrate a drying technology suitable for small-scale processors of dried fruits and vegetables in non-electrified areas of developing countries. Key features of the biomass burner were found to be the addition of thermal mass on the upper surface, an internal baffle plate to lengthen the exhaust gas exit path and a variable air inlet valve. Further modifications to further improve the performance of both the solar and biomass components of the dryer were also suggested [53]. A new natural convection solar dryer consisting of a solar air heater and a drying chamber was developed by Pangavhane et al. This can be used for drying various agricultural products like fruits and vegetables. The qualitative analysis showed that the traditional drying, i.e. shade drying and open sun drying, dried the grapes in 15 and 7 days respectively, while the solar dryer took only 4 days and produced better quality raisins [54]. A direct type natural convection solar dryer was designed, constructed using local materials (wood, blades of glass, and metals) and then tested experimentally in foodstuffs drying (cassava, bananas, and mango) by Gbaha et al. It was about an experimental approach which consists in analyzing the behavior of the dryer and it relates mainly kinetics and establishment of drying heat balances [55].

3.2. Greenhouse solar dryers

The greenhouse solar system (bulk-curing/greenhouse system or solar barn) is a large solar collector in which the curing and drying process or plant production process takes place for effective year-round solar energy utilization in agricultural production. The microcomputer control of tobacco bulk curing process with such a system was implemented by Huang and Toksoy and successfully applied to maximize solar energy utilization. Growth and yield studies had shown that solar barn grown seedlings adapted to fully automatic transplanting and that a better growth and yield was achieved from these seedlings. The simulation results of system concept, theoretical considerations, mathematical models and analyses presented for the solar drying mode operation agreed favorably with the measured data [56]. Janjai et al. presented the experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. A system of partial differential equations describing heat and moisture transfer during drying of peeled longan and banana in the solar greenhouse dryer was developed and this system of non-linear partial differential equations was solved numerically using the finite difference method. The numerical solution was programmed in Compaq Visual FORTRAN version 6.5. This model can be used to provide the design data and is also essential for optimal design of the dryer [57]. Jain presented a transient analytical model to study the application of a greenhouse with packed bed thermal storage to crop drying and evaluated the performance of an even shape greenhouse with a packed bed and crop dryer for drying of onions. Here, the parametric study involved the effects of length and breadth of the greenhouse and mass flow rate of air on the temperature of crop [58]. A conventional greenhouse solar dryer of $6\,m^2 \times 4\,m^2$ floor area (east–west orientation) was improved by Sethi and Arora for faster drying using inclined north wall reflection (INWR) under natural as well as forced convection mode. By using the north wall reflection principle, the product fully received the reflected beam radiation (which otherwise leaves through the north wall) in addition to the direct total solar radiation available on the horizontal surface during different hours of drying. This enhanced the drying rate of the product by increasing the inside air temperature and crop temperature of the dryer [59].

3.3. Indirect type solar dryer

Sharma et al. described the design and performance of an indirect type solarfruit and vegetable dryer developed at Area Energetica, Dipartimento SIRE, Divisione Ingegneria Sperimentale of ENEA-C.R.E, Trisaia and the experimental results suggested that even under unfavorable fall weather conditions, the unit is able to produce good quality products and due to the low investment required, the solar dryer is predestined for applications on small farms [60]. A new specific prototype of an indirect active hybrid solar–electrical dryer for agricultural products was constructed and investigated at LENREZA Laboratory, University of Ouargla (Algerian Sahara) by Boughali et al. Experimental tests with and without load were performed in winter season in order to study the thermal behavior of the dryer and the effect of high air mass flow on the collector and system drying efficiency and the fraction of electrical and solar energy contribution versus air mass flow rate was investigated. An economic evaluation was calculated using the criterion of payback period which was very small 1.27 years compared to the life of the dryer [61]. An indirect type natural convection solar dryer was designed so as to be able to insert various storage materials under the absorber plate in order to improve the drying

process, constructed and investigated experimentally by El-Sebaii et al., under Tanta prevailing weather conditions. Drying experiments were conducted with and without storage materials for different spherical fruits, such as seedless grapes, figs and apples, as well as vegetables, such as green peas, tomatoes and onions and the solar irradiance, temperature distribution in different parts of the system, ambient temperature and relative humidity of the inlet and outlet drying air were recorded. It was also found that the storage and chemical pretreatment caused significant decrease in the drying time for all the investigated crops [62]. The energy and exergy analyses of the drying process of olive mill wastewater (OMW) using an indirect type natural convection solar dryer were presented by Celma and Cuadros and it was found that the exergetic efficiencies of the drying chamber decreased as inlet temperature was increased, provided that exergy losses became more significant [63]. An indirect type natural convection solar dryer with integrated collector-storage solar and biomass-backup heaters was designed, constructed and evaluated by Madhlopa and Ngwalo. The dryer was fabricated using simple materials, tools and skills, and it was tested in three modes of operation (solar, biomass, and solar–biomass) by drying twelve batches of fresh pineapple (*Ananas comosus*), with each batch weighing about 20 kg. Results showed that the thermal mass was capable of storing part of the absorbed solar energy and heat from the burner. The average values of the final-day moisture-pickup efficiency were 15%, 11%, and 13% in the solar, biomass, and solar–biomass modes of operation respectively [64]. The performance of indirect passive solar dryers tends to be rather poor because of the low air flow rates which occur through such dryers. Two ways to improve the performance of such dryers are; to use waste fuel to increase the buoyancy forces by heating the air in a chimney attached to the dryer, and to reduce the air gap between the upper transparent cover and the absorber plate in the collector in order to increase heat transfer to the air. Bassey et al. presented the results of an experimental study in which the effects of heating the air in a chimney fitted to the dryer and the effects of varying the collector gap on the dryer performance were measured and the results indicated that the performance of the dryer can be improved if temperatures in the chimneys are maintained over 50 °C above the ambient for more than 4 h and if the chimney is at least 2 m high and the mean drying rates in the dryer can also be improved by reducing the collector air gap height which should not be greater than 4 cm [65].

3.4. Indirect multi-shelf solar dryers

Design details and the performance studies carried out with indirect type multi-shelf fruit and vegetable dryer were reported by Sharma et al. Experimental results for drying a variety of fruits with and without chemical pretreatment and under different drying conditions were analyzed and in drying the fruits it was observed experimentally that use of chemical pretreatment offers not only a significant increase in drying rate but also higher dryer efficiency with better quality dried end product [66]. Singh et al. developed a solar dryer, which has a multi-shelf design with intermediate heating, passive, integral, direct/indirect and portable solar dryer, to enable farmers to add value to their produce by drying it at the farm itself and can also be used in cottage industries in remote places, with a novel feature of drying the product under shade or otherwise as per requirement. To overcome the problem of reduction in efficiency on second and third drying day, a semi-continuous mode of loading was investigated, in which the efficiency remains almost the same on all drying days and the shelf life of the dried product is more than one year [67]. Singh et al. developed and tested a natural convection solar dryer having multi-shelf design, consisting of three perforated trays arranged one above the other, which can be used for drying various products at home under hygienic conditions with the self guarantee of adulteration free product. It had two novel features, namely, the variable inclination to capture more solar energy in different seasons and the option to dry products under shade or without shade as per requirement [68].

3.5. Cabinet type solar dryers

A drying system was constructed and tested by Al-Juamily et al., consisting of three parts (solar collector, solar drying cabinet, and air blower) and the results showed that the most effective factor on the drying rate is the temperature of the air inside the cabinet; the effect of variation of speed of air inside the drying cabinet is small and can be neglected and the relative humidity of air leaving the cabinet was small (between 25% and 30%) and therefore there is no need for high velocity air inside the cabinet [69]. A transient analysis of a cabinet-type solar dryer was carried out by Dutta et al., with simplified but practical assumptions and the model predicts the instantaneous temperatures inside the dryer, the moisture content and the drying rates. The analysis was done for no load, and for loads ranging from 10 kg to 40 kg of drying product [70]. An attempt was made by Sharma et al. to analyze a cabinet type solar dryer, by writing the transient equations for the different components of the system and their solutions attempted within the framework of periodic analysis. The model was capable of predicting the instantaneous temperature inside the dryer, the moisture content and drying rates and the results obtained from the theoretical and experimental observations were reported [71]. The development and testing of a new type of efficient solar dryer, with two compartments: one for collecting solar radiation and producing thermal energy and the other for spreading the product to be dried, particularly meant for drying vegetables and fruit, was described by Sreekumar et al. A detailed performance analysis was done by three methods, namely 'annualized cost method', 'present worth of annual savings', and 'present worth of cumulative savings' and the drying cost for 1 kg of bitter gourd was calculated as Rs. 17.52, whereas it was Rs. 41.35, in the case of an electric dryer [72]. The reverse flat-plate absorber is a non-concentrating collector which can collect solar energy at high temperature, unlike conventional non-concentrating collectors. The concept of a reverse flat plate collector was used by Goyal and Tiwari as a heating medium of air for drying agricultural products in a cabinet dryer. The thermal performance of the new proposed dryer was analyzed by solving the various energy balance equations and compared with that of a conventional cabinet dryer. It was found that the reverse flat-plate absorber dryer gave the better performance [73].

3.6. Tunnel type solar dryers

The modeling and thermal performance results of the collector of a semi-cylindrical Solar Tunnel Dryer (STD), was presented by Garg and Kumar. The performance was estimated under natural circulation as well as under forced circulation mode and also calculated for different tilts of the STD, for Delhi climate (28.58°N Latitude). The development of the natural circulation type STD is very significant because it has certain advantages over the existing forced circulation type STD [74]. A multi-purpose solar tunnel dryer consisting of a small centrifugal blower, a collector and a tunnel drying chamber, originally developed for use in arid zones, was modified by Amir et al., to enable operation under tropical weather conditions, with a biomass furnace and heat exchanger integrated into the solar drying system to heat the drying air during cloudy and rainy days. Results showed that compared to natural sun drying, the drying time of cocoa, coffee and coconut could be reduced up to 40% and investigations further showed that even during the rainy season it was possible to dry the products to the final moisture

content which is needed for storage and marketing and the modular system allows adaptation to different farm sizes as well as cooperative use [75].

3.7. Integral type solar dryers

A comprehensive study of the behavior of a large-scale integral-type natural-circulation solarenergy dryer suitable for use in the tropics was performed by Ekechukwu and Norton, over the entire range of weather conditions encountered in a typical tropical climate. The design, construction and installation of the dryer and its measured transient performance were reported and linear correlations of measured data for a grouped parameter of ambient and crop properties against moisture content was obtained. This may form the basis for the development of solar dryer design charts [76]. A comprehensive comparative analysis of the measured performance of a large scale integral type natural-circulation solar-energy crop dryer suitable for use in the tropics was presented by Ekechukwu and Norton for the two prevalent tropical wet and dry seasons and the performance of the dryer studied was dependent largely on the variations in insolation, ambient temperature and relative humidity. The drying conditions during the dry season were fairly constant (yielding a comparatively better performance), while the wet season drying conditions were more unpredictable and resulted in poorer drying [77]. The integral-type natural-circulation solar crop dryer was simulated by Onyegegbu et al., to include the effects of varying ambient conditions of air temperature and humidity and diffuse and beam components of solar radiation and it was shown that operating the dryer at conditions of minimum entropy generation yields a useful criterion for choosing dryer dimensions and is compatible with the desire to maintain allowable limits on crop temperature [78]. Sharma et al. furnished the necessary information to correctly design a solar air heating system that can be used for residential or agricultural applications. An inexpensive augmented integrated solar collector cum storage system using rocks as a sensible heat storage medium was designed and fabricated to provide low grade heat to suit the needs of space heating and agricultural applications and the experimental observations of fluid temperature, energy storage and other measures of system performance were also presented [79].

3.8. Mixed mode natural convection solar dryers

A mathematical model, consisting of the air-heating process model, the drying model and the technical performance criteria model, for drying agricultural products in a mixed-mode natural-convection solar crop dryer (MNCSCD) using a single-pass double-duct solar air-heater (SPDDSAH) was presented by Forson et al. The governing equations of the drying air temperature and humidity ratio; the material temperature and its moisture content; and performance criteria indicators were derived. Results of simulation runs using the model were presented and compared with the experimental data and it was shown that the model can predict the performance of the MNCSCD fairly accurately and therefore can be used as a design tool for prototype development [80]. A mixed-mode natural-convection solar crop dryer (MNCSCD) designed and used for drying cassava and other crops in an enclosed structure was presented by Forson et al. A prototype of the dryer was constructed to specification and used in experimental drying tests. The systematic combination of the application of basic design concepts, and rules of thumb resulting from numerous and several years of experimental studies used were outlined and the results of calculations of the design parameters were presented [81].

3.9. Solar chimney dryer

Ferreira et al. studied the feasibility of a solar chimney to dry agricultural products. To assess the technical feasibility of this drying device, a prototype solar chimney, in which the air velocity, temperature and humidity parameters were monitored as a function of the solar incident radiation, was built and the drying tests of food, based on theoretical and experimental studies, assured the technical feasibility of solar chimneys used as solar dryers for agricultural products [82]. An experimental investigation into the performance of a solar crop dryer with solar chimney and no air preheating was described by Afriyie et al. Tests were performed on the cabinet dryer, using a normal chimney and repeated with a solar chimney, the trials were carried out with the roof of the drying chamber inclined further to form a tent dryer. The results showed that the solar chimney can increase the airflow rate of a direct-mode dryer especially when it is well designed with the appropriate angle of drying-chamber roof [83]. Das and Kumar described the detailed design and performance of a prototype, low cost and simple solar dryer coupled with a vertical flat plate collector chimney for drying 20 kg of field harvest high moisture paddy. The experiments during the winter months showed an average rise of air temperatures of 21.8 °C and 27.1 °C for the inclined and the vertical collectors, respectively, with an average air flow rate of 0.6707 m^3/min (0.22 m/s) through the chimney and a 33% reduction in air flow rate was observed with 7 cm depth of grain (20 kg) in the dryer, when the average rise of air temperature in the inclined collector was increased to 68.5 °C [84].

3.10. Back-pass and multi-pass solar dryer

A prototype solar drying system was designed and tested by Othman et al. in the Universiti Kebangsaan Malaysia campus and the study showed that the system can be upgraded by improving the solar collector. The preliminary result on the performance of the V-groove back-pass solar collector modified from V-groove double flow solar collector designed earlier showed that the collector maintained the output temperature even though there are changes in solar radiation intensity [85]. The double-pass solar collector with porous media in the lower channel provides a higher outlet temperature compared to the conventional single-pass collector. Therefore, the thermal efficiency of the solar collector is higher. A theoretical model was developed and an experimental setup was designed and constructed for the double-pass solar collector by Sopian et al. Comparisons between the theoretical and the experimental results concluded that the presence of porous media in the second channel increases the outlet temperature, therefore increases the thermal efficiency of the systems [86]. Jain and Jain presented a transient analytical model for an inclined multi-pass solar air heater with in-built thermal storage and attached with the deep-bed dryer and evaluated the performance of a solar air heater for drying the paddy crop in a deep bed by using an appropriate deep-bed drying model. The effect of change in the tilt angle, length and breadth of a collector and mass flow rate on the temperature of grain were studied; the rate of moisture evaporation and humidity of the drying air were analyzed with the drying time for different depth of the grain bed. It was observed that the bed moisture content decreases with the time of the day and the humidity of the air and the drying rate increases with the increase in the depth of drying bed [87]. Jain presented a periodical analysis of multi-tray crop drying attached to an inclined multi-pass solar air heater with in-built thermal storage. The performance of multi-tray drying integrated with a solar air heater was evaluated for drying of the paddy crop. The thin layer drying equation was used to study the drying rate and hourly reduction in moisture content in the different trays and it was observed that the crop moisture content

decreases with the drying time of the day. Different drying rates were observed in different drying trays due to the variation in crop temperatures and it was observed that the thermal efficiency of the drying increases with increase in mass of the crop [88].

3.11. Low cost domestic and industrial solar dryers

A low-cost solar air heater, consisting of a frame which is fixed on the ground, a transparent cover foil and black plastic as absorber, for the drying of agricultural products in tropical countries was developed and tested by Esper et al. The tests showed that the recorded temperature rise of up to 50 K is sufficient to dry various agricultural products at optimum conditions. Compared to solar air heaters commercially produced in industrialized countries, the investment costs as well as the air resistance of the plastic film collectors were significantly lower, which can be produced either by small scale industries or by farmers themselves using simple tools and locally available materials, favoring their use in tropical and subtropical countries [89]. Ahmad built a simple solar air heater from cheap plastic wrapping film with air bubbles, for use in drying operations on a farm (grain, fruit, fish, etc.). The model used was a single-sheet cylindrical collector and, after it gained some heat, another layer of the plastic wrapping film with air bubbles was added at a later stage to decrease convection heat losses to the surroundings. Although the method used was simple, a considerable gain in the temperature of the airflow was obtained: a temperature difference of around 10 °C was measured [90]. A domestic solar dryer with transparent external surfaces was designed, built and tested by Saleh and Badran. A solar dryer with a uniform temperature profile that meets the requirements of the exponential model over a wide range of cases, thus, providing a simple and accurate design tool was proposed. This was characterized by collecting the maximum possible solar energy by having a longer drying period, and allowed the fixed dryer to approach the performance of the tracked dryer with all the technical and economic advantages of the tracking system. The performance was tested under different operational conditions and the drying characteristics were experimentally investigated by conducting the experiments on two local herbs; Jew's mallow and mint leaves [91]. A new solar dryer, which consisted of a solar air heater and a drying chamber, was developed by Tiris et al., for drying food products and was successfully tested using sultana grapes, green beans, sweet peppers, and chilli peppers. The traditional sun-drying experiments were employed and compared with the solar-drying experiments and it was shown that the use of this type of solar dryer reduced the drying time significantly and essentially provided better product quality [92]. Industrial drying may prove to be an economical application of solar energy when the process utilizes stored energy when sunshine is not available. A simple system was evolved by Khanna and Singh, wherein a reservoir and heat exchanger were incorporated into the drying system. Solar heat collection and storage were effected by thermo-siphon action with water and depending on the mode of heat transfer, viz. natural or forced convection, the system can be used either for space heating or indoor industrial drying with solar energy [93]. A multi-purpose solar crop dryer, consisting of a small fan, a solar air heater and a tunnel dryer, was developed by Lutz et al., for drying various agricultural products such as fruits, vegetables, medicinal plants, etc. The simple design of this dryer allows production either by farmers themselves, using cheap and locally available materials, or by small scale industries and due to the low investment required, the solar dryer is predestined for application on small farms in developing countries. The solar dryer was successfully tested in Greece, Yugoslavia, Egypt, Ethiopia, and Saudi Arabia drying grapes, dates, onions, peppers, and several medicinal plants. On-farm tests also showed that the dryer can be easily operated by farmers [94].

3.12. Solar timber kilns

Numerical simulation and experimental measurement were used by Taylor and Weir, to examine the performance of a glasshouse-type solar timber dryer, which dries about 5 m^3 of timber from green to equilibrium in about 3 weeks. It was found that fastest drying is obtained from a design with low heat capacity but good (forced) circulation of air through the timber stack [95]. Analysis of the evolution in solar heated drying kilns in recent decades shows that there have been a series of modifications to optimize their thermal and drying efficiency. Using an analysis method based on product design, Luna et al. reported on existing solar timber kilns; the different dryers and their component units were studied; developments were noted, focusing on changing trends in technological systems and as a result of this analysis some future adaptations were suggested [96].

4. Drying in off sunshine hours

A transient analytical model was presented by Aboul-Enein et al., for a flat-plate solar air heater with and without thermal storage. Assuming the flowing air temperature to vary with time and space coordinates, the effects of design parameters of the air heater such as length (L), width (b), gap spacing between the absorber plate and glass cover (d_f), mass flow rate and thickness and type of the storage material (sand, granite and water) on the outlet and average temperatures of the flowing air were studied. Improvements in the heater performance with storage were achieved at the optimum thickness (0.12 m) of the storage material, which facilitates the use of the air heater as a heat source for drying agricultural products and the drying process can be continued during night, instead of re-absorption of moisture from the surrounding air [97]. The design, construction and performance evaluation of a passive solar powered air heating system, consisting of a single-glazed flat plate solar collector integrated with a phase change material (PCM) heat storage system to enable operation at night and which has potential applications in crop drying and poultry egg incubation, was presented by Enibe. The results showed that the system can be operated successfully for crop drying applications and with suitable valves to control the working chamber temperature, it can also operate as a poultry egg incubator [98]. A new design of thin layer bed crop drying cum water heater was proposed and analyzed by Tiwari et al., for making the whole system operate throughout the year. The system can be used to provide hot water when the drying system is not in operation and the water heater below the air heater systems would act as a storage material for drying the crop during off sunshine hours [99]. A prototype solar fruit and vegetable dryer was developed by Akyurt and Selcuk, comprising a glass covered flat plate collector containing metal chips, a dryer with translucent walls, and an insulated tunnel, joining the two. Bell peppers and sultana grapes were dried to commercially acceptable moisture levels in various kinds of weather conditions and at various air velocities. An economic analysis was undertaken to investigate the possibility of using various heat sources for an auxiliary heating system, which when integrated with the prototype, will enable all-weather operation [100].

4.1. Desiccant based drying systems for night operation

Drying with solar-heated air is satisfactory as long as the sun is shining. To continue this process through the night and periods of cloud cover, it is necessary to either store some of this energy in a thermal mass or incorporate desiccants within the drying

system. Thoruwa et al. reported the results from studies undertaken to develop three low cost solar regenerative clay–$CaCl_2$ based solid desiccant materials. They established their moisture sorption and regeneration characteristics; assessed their performance when compared with commercial desiccants and the integration of these within a low cost solar drying system for small-scale village-based crop drying. The results showed that the bentonite–$CaCl_2$ (type 1) desiccant gave a maximum moisture sorption of 45% dry weight basis (DWB) while bentonite–$CaCl_2$ (type 2) and kaolinite–$CaCl_2$ (type 3) solid desiccants each gave moisture sorption values of 30% (DWB). It was concluded from the moisture sorption and regeneration characteristics that their application in solar crop drying and air dehumidification is highly useful due to their low regeneration temperatures (sub 100 °C) [101]. An indirect forced convection solar dryer with integrated desiccants was built and tested by Shanmugam and Natarajan, with four main parts namely a flat-plate solar air collector, a drying chamber, desiccant bed and a centrifugal blower. The system was operated in two modes, sunshine hours and off sunshine hours, and drying experiments were conducted with and without the integration of desiccant unit. The effect of a reflective mirror on the drying potential of the desiccant unit was also investigated and the results showed that the inclusion of reflective mirror on the desiccant bed causes faster regeneration of the desiccant material [102]. An indirect forced convection and desiccant integrated solar dryer, consisting of a flat-plate solar air collector, drying chamber and a desiccant unit, was designed and fabricated by Shanmugam and Natarajan to investigate its performance under the hot and humid climatic conditions of Chennai, India, with green peas. The system pickup efficiency, specific moisture extraction rate, dimensionless mass loss, mass shrinkage ratio and drying rate were discussed [103]. The mathematical model for the Kathabar Spray-Cel System developed by Mahmouda and Ball was used to predict the temperature and humidity ratio of the air at the drying bin inlet. The existing unsteady grain cooling model was modified and coupled with the liquid desiccant system model to study the feasibility of using the system desiccated air in drying applications and the model showed the infeasibility of using desiccated air for grain drying. The liquid desiccant system was modified to simulate adiabatic operation and coupled to the drying model and the new system gave much better results, but its use for grain drying was predicted to be economically unfeasible [104]. An adsorption unit of silica gel was designed by Hodali and Bougard and integrated in a crop solar drying installation, consisting of a direct flat-plate forced convective solar dryer connected with a similar solar collector. The daily sorption cycle of the desiccant unit was first investigated and a suitable coupling of the collector, the dryer and the adsorption unit were selected and numerically simulated and applied to the drying of apricots in Morocco under real climatic conditions. The integration of the adsorption unit improved the quality of the dried product and permitted a cyclic operation of drying over two days by reducing the drying period from 52 h to 44 h [105]. Thoruwa et al. described some of the performance aspects of an autonomous solar desiccant maize dryer developed for village use in Kenya. Since most commercial desiccants were expensive, a low cost solid desiccant was fabricated from bentonite clay and calcium chloride materials, which is capable of regeneration at 45 °C, has high moisture sorption of 45% (DWB), significantly extends the drying process at night and reduces aflatoxin contamination of the grain. Laboratory and field testing were performed to determine the drying performance and the results showed that the prototype dryer had the capability of drying 90 kg of fresh maize from 38% (DWB) to 15% (DWB) within 24 h [106]. Punlek et al. made a simulation design for a hybrid PV/T assisted desiccant integrated HA-IR drying system (HPIRD) which had two components: a photovoltaic air collector (PVAC), and a desiccant silica gel bed (DB). The two new models were used to develop a new drying system and compared with a common system. The simulation results indicated that the $PVAC_{AF}$ and v-shape DB were suitable, and they also indicated consistent results when compared with the experiment. The drying time, drying rate and energy consumption were reduced considerably with the hybrid drying system [107].

5. Solar grain dryers

A solar grain dryer with photovoltaic powered air circulation was designed, developed and tested in the field by Mumba. The dryer was found to be cost-effective with a payback period of less than one year and when compared to the traditional sun drying method, drying with this dryer was found to be a viable option with many benefits, such as a protected drying environment, improved dried product quality and increased throughput. The dryer was suitable for rural farm applications where grid electricity and fossil fuel are either nonexistent or extremely expensive for the average farmer [108]. The optimum method for using a solar air collector combined with a grain drying system was investigated by Radajewski et al., with two types of solar collectors, integrated into a roof; one uncovered (flow under absorber) and one covered (flow over absorber). A computer model was developed to minimize the cost of drying and in doing so optimize the geometry of the collector and the specific rate of air flow through the collector. The results showed an optimum number of hours of operation per day, optimum drying temperature and optimum initial moisture content for any combination of the other variables and the most critical factors affecting annual savings are the length of the drying season and the specific cost of the collector [109]. The use of a combined solar heat pump rice drying system was being developed as an alternative to conventional mechanical dryers and evaluated by Best et al. The experimental equipment developed was a modified 7 kW R-22 air conditioning unit and was combined with a solar collector for a more precise control of temperature and humidity [110]. Thin-layer solar drying experiments were conducted at Matsuyama, Japan, with medium grain rough rice by Basunia and Abe, using a mixed-mode natural-convection solar grain dryer. The data of sample weight and dry-bulb and wet-bulb temperatures of the drying air were recorded continuously from morning to evening for each test and were then fitted to the Page model, based on the ratios of the differences between the initial and final moisture contents and the equilibrium moisture content (EMC) [111]. Zaman and Bala presented a set of simple empirical equations for natural air flow solar drying of rough rice in mixed-mode type dryer, box-type dryer and open floor drying system. The effect of drying air temperature on the drying rate constants for these three cases were found to be insignificant and the equilibrium moisture content appeared to be the most important variable controlling the drying rate. The highest drying rate was observed in case of mixed-mode dryer and the drying rate of box dryer was next to that of mixed-mode dryer [112]. A mathematical model to simulate the indirect natural-convection solar drying of rough rice was presented by Bala and Wood. The variation of the air temperature in the collector and across the air bed was incorporated in the prediction of the thermal buoyancy effect and the results showed that at low air flow rates produced by natural-convection, the drying wave moves slowly and the layer of grain cannot be considered uniform, with serious over-drying taking place in the bottom layer. Sensitivity analysis showed the system to be most sensitive to grain bed depth and collector length and least to chimney height and cover to absorber spacing [113]. A procedure for determining the optimum collector area for a solar paddy drying system was developed by Janjai et al., which is applicable for a forced-convection drying system operating without auxiliary heat source. In developing the procedure, a simulation model was developed and used for analyzing

the system performance. Two correlation parameters, P and Q, which are functions of system parameters and weather data were formulated and combined with a drying cost analysis, the correlation provides a method by which solar designers can determine the optimum collector area for the solar paddy drying system [114]. A new approach for employing solar radiation as the main source of energy for paddy drying was introduced by Zomorodian et al. The drying test rig, consisting of six ordinary solar air heaters, an auxiliary electric heating channel, a drying chamber with an electric rotary discharging valve and an air distributing system, was designed, fabricated and evaluated. The rough rice solar dryer was a cross flow and an active mixed-mode type with a new and an efficient timer assisted semi-continuous discharging system. To evaluate the drying system, a local variety of medium size kernel of rough rice was selected to be dried by the dryer and the effect of mass flow rate and interval time of crop discharging on the rate of crop drying by the dryer was also evaluated [115]. Simate presented a comparison of optimized mixed-mode and indirect-mode natural convection solar dryers for maize and the mixed-mode and indirect-mode solar drying simulation models were validated against results from a laboratory solar dryer with experiments carried out under a solar simulator at the University of Newcastle upon Tyne, UK. The drying cost, annual cost and initial cost of the mixed-mode dryer were lower than those of the indirect-mode although the quantity of dry grain obtained from the mixed-mode for the whole year is less than for the indirect-mode; the drying costs are 12.76 and 16.05 USD/ton for mixed-mode and indirect-mode dryers, respectively [116]. An experimental simulation of a grain drying system was tested by Tiwari et al. and the experimental observations were used to evaluate the drying time for wheat crop of given moisture content. The effect of storage was also included in the present design and it was observed that the fluctuation in temperature is significantly reduced due to the storage effect [117]. The possible savings in electrical energy that could result from adding a solar collector to an ambient-air in-bin grain dryer for wheat and corn (maize) in the main grain-growing regions of Canada were predicted using an equilibrium drying model by Fraser and Muir [118]. A modern unit for drying grains after harvesting was investigated by Tayeb. Design steps of the unit are given in detail and the performance was tested with corn and peanuts and found satisfactory [119]. Roa and Macedo presented the results from the drying of 600 kg of "carioca" dry beans in a round bin with a perforated floor, using solar energy as the only supplementary heat source. The performance of the flat-plate collectors and the drying data were analyzed with the basic equations of transfer complemented with newly proposed empirical equations describing thin layer drying and equilibrium data [120].

5.1. *Fruit dryers and characteristics of fruits while drying*

Koua et al. investigated the behavior of the thin layer drying of plantain banana, mango, and cassava experimentally in a direct solar dryer and performed mathematical modeling by using thin layer drying models encountered in literature. Seven statistical models, which were empirical or semi-empirical, were tested to validate the experimental data. The Henderson and Pabis drying model was found to be the most suitable for describing the solar drying curves of plantain banana, mango and cassava and the drying data of these products were analyzed to obtain the values of the effective diffusivity during the falling drying rate phase [121]. Both a heat pump and solar dryer were designed, manufactured and experimentally analyzed by drying apples, and a comparison was made between the two by Aktas et al. For both systems, the moisture ratio was analyzed with the Statgraphics program by using semi-theoretical models and compared with the empirical values; correlation coefficients of the equations were calculated and standard error of estimation (SEE) and R^2 values were obtained [122]. Sarsilmaz et al. investigated the drying of apricots in a newly developed rotary column cylindrical dryer (RCCD) equipped with a specially designed air solar collector (ASC) to find the optimum drying air rate and rotation speed of the dryer, to maintain uniform and hygienic drying conditions and to reduce drying times. A type of apricots dried in the present dryer were compared to those of the same type of apricots dried open on the ground and it was shown that co-operation of RCCD and ASC increased drying rate, reduced drying times and rotation of drying chamber provided gains in both time and labor [123]. Solar drying experiments in thin layers of apricots grown in Elazig, Turkey, were conducted using an indirect forced convection solar dryer consisting of a solar air heater with conical concentrator and a drying cabinet by Togrul and Pehlivan. Drying curves obtained from the data were fitted to a number of mathematical models and the effects of drying air temperature, velocity and relative humidity on the model constants and coefficients were evaluated by the multiple regression and compared to previously given models. The logarithmic drying model was found to satisfactorily describe the solar drying curve of apricots with a correlation coefficient (r) of 0.994 [124]. A hybrid solar dryer was designed and constructed using direct solar energy and a heat exchanger by Amer et al. The efficiency of the solar dryer was raised by recycling about 65% of the drying air in the solar dryer and exhausting a small amount of it outside the dryer and the solar dryer was tested for drying of ripe banana slices [125]. Smitabhindu et al. presented a mathematical model for optimal design of a solar -assisted drying system for drying bananas. The optimization model consisted of a simulation model of a solar-assisted drying system combined with an economic model. A computer program in FORTRAN was developed to simulate the performance of the drying system and the model was validated by comparing the simulation results with the experimental results and they were in good agreement [126]. Drying of cassava chips (a major staple food in many African countries) under natural conditions constitutes a major problem in a humid climate. A study was conducted in Ibadan in the humid zone of Nigeria by Olufayo and Ogunkunle, to assess the rate of drying of cassava under different natural conditions. The sunshine hours, daytime temperature and relative humidity were recorded during collections of samples, in order to study their influence on drying and there were no significant variations in the drying patterns of chips dried at about equal weight per unit area; the thickness of the layer of chips had significant effects on the nature and pattern of drying and the use of locally constructed solar dryers appeared to be the most promising [127]. Doymaz investigated the sun drying behavior of figs. Drying experiments were conducted for figs (*Ficus carica*) grown in Iskenderun-Hatay, Turkey, and the drying data were fitted into different mathematical models such as Lewis, Henderson and Pabis, Page, Logarithmic, Two-term, Two-term exponential, Verma et al. and Wang and Singh models, the performance of these models were investigated by comparing the determination of coefficient (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) between the observed and predicted moisture ratios. The results showed that the Verma et al. model satisfactorily described the sun drying curve of figs with a R^2 of 0.9944, χ^2 of 0.000483 and RMSE of 0.062857 [128]. Field level experiments on solar drying of pineapple using solar tunnel dryer were conducted at Bangladesh Agricultural University, Mymensingh, Bangladesh by Bala et al. The pineapple dried in the solar tunnel dryer were completely protected from rain, insects and dust, and its quality was comparable to sun dried products. The proximate analysis also indicated that the pineapple dried in the solar tunnel dryer was of a quality suitable for human consumption [129]. Prunes produced by drying plums are a healthy and tasty human diet rich in nutrition. Drying plums is a slow and energy-intensive process because of its waxy skin that has low

permeability to moisture. Stanley plums in sample bags were dipped in one of four different pretreatment solutions (4% ethyl oleate, 1% KOH, 1% NaOH, or water) at two different dipping temperatures (23 °C and 60 °C) for 1 min to accelerate the skin moisture diffusivity by breaking down the waxy cuticular surface of plum for investigation by Tarhan. After the completion of the pretreatment process, the plum samples were dried at low or moderate temperatures (<55 °C) of drying air. Solar drying and open sun drying of plums treated by 1% KOH or 1% NaOH at 60 °C dipping temperature completed approximately in 177 h and 250 h [130]. Thin layer solar forced drying experiments were conducted for strawberries (*Fragaria Xananassa*) of the Chandler variety by El-Beltagy et al. Different shapes of strawberry (whole, halves quarter, and 3 mm discs) pretreated with different solutions: (1) 1% sodium metabisulphite + 1% citric acid (Tr. A), (2) 1% ascorbic acid + 1% citric acid (Tr. B), (3) 1% citric acid (Tr. C), (4) 2% sodium metabisulphite (Tr. D). The results showed that a (Newton) term drying model could satisfactorily describe the solar drying curve of strawberry and pretreatment and slicing did not affect the chemical composition of strawberry [131]. Akbulut and Durmus had done the energy and exergy analyses of the thin layer drying process of mulberry via forced solar dryer. The drying experiments were conducted at five different drying mass flow rates varied between 0.014 kg/s and 0.036 kg/s and the effects of inlet air velocity and drying time on both energy and exergy were studied. From the results, it was concluded that both energy utilization ratio and exergy loss decreased with increasing drying mass flow rate while the exergetic efficiency increased [132]. The thin layer solar drying experiments of organic tomato using solar tunnel dryer were conducted under the ecological conditions of Ankara, Turkey by Sacilik et al., with organic tomatoes. A non-linear regression procedure was used to fit 10 different thin layer mathematical models available in literature to the experimental drying curves and these curves showed only a falling drying rate period. The models were compared using the coefficient of determination, mean relative percent error, root mean square error and the reduced chi-square and the approximation of diffusion model showed a better fit to the experimental drying data when compared to other models [133]. Midilli and Kucuk presented a mathematical modeling of thin layer forced and natural solar drying of shelled and unshelled pistachio samples. Eight different mathematical models, which are semi-theoretical and/or empirical, were applied to the experimental data and compared according to their coefficients of determination (r, χ^2), which were predicted by non-linear regression analysis using the Statistica computer program, for estimating and selecting the suitable form of solar drying curves and it was deduced that the logarithmic model could sufficiently describe thin layer forced solar drying of shelled and unshelled pistachio, while the two-term model could define thin layer natural solar drying of these products in evaluation [134]. An experimental closed-type dryer associated with a photovoltaic system (*PV*) was developed with the transparent drying cabinet being designed with high transmittance glass to decrease the reflection of direct sunlight and to offer extra direct solar heating onto the raw material during drying. Lemon slices were dried using the closed-type solar dryer and results were compared with hot air drying at 60 °C and the results indicated that the dried lemon slices using a closed-type solar dryer has better general levels of quality in terms of sensory parameters [135]. Lahsasni et al. presented the thin layer convective solar drying and mathematical modeling of prickly pear peel, using an indirect forced convection solar dryer consisting of a solar air collector, an auxiliary heater, a circulation fan and a drying cabinet. The experimental drying curves showed only a falling drying rate period and the main factor in controlling the drying rate was found to be the drying air temperature. The experimental drying curves obtained were fitted to a number of mathematical models and the Midilli–Kucuk drying model was found to satisfactorily describe the solar dryingcurves of prickly pear peel with a correlation coefficient (r) of 0.9998 and chi-square (χ^2) of 4.6572×10^{-5} [136].

5.2. Grape drying

Jairaj et al. reviewed various solar dryers developed exclusively for drying grapes on a normal scale. Many popular varieties of solar dryers, certain typical models as well as traditional methods practiced for drying grapes were presented and the technical and economical results proved that solar drying of grapes is quite feasible and the fact that commercialization of solar drying of grapes has not gained momentum as expected may be due to high initial investment and low capacity of the dryers [137]. Pangavhane and Sawhney reviewed the development trends of solar dryers used for drying grapes. Several typical installations, including traditional methods, were presented and the technical and economical results indicated that solar drying of grapes is feasible but the farmer's acceptance of solar drying was still very limited, which may be due to the small capacity of the dryers and long payback period or due to socio-cultural factors [138]. Fadhel et al. analyzed the drying of the Sultana grape variety by three different solar processes, by establishing three drying kinetics; in a natural convection solar dryer, under a tunnel greenhouse and in open sun. These tests showed that the solar tunnel greenhouse drying is satisfactory and competitive to a natural convection solar drying process [139]. A hybrid photovoltaic-thermal (*PV/T*) greenhouse dryer of 100 kg capacity has been designed and constructed at Solar Energy Park, Indian Institute of Technology, New Delhi (28°35′N, 77°12′E, 216 m above MSL), India, for drying the Thompson seedless grapes (*Mutant: Sonaka*). The drying of grapes was also performed in open as well as shade for comparison and various hourly experimental data namely moisture evaporated, grape surface temperatures, ambient air temperature and humidity, greenhouse air temperature and humidity, etc. were recorded to evaluate heat and mass transfer for the proposed system [140]. Thin layer solar drying experiments were conducted for Sultana grapes (cv. Thompson seedless) grown in Antalya, Turkey, using an indirect forced convection solar dryer consisting of a solar air heater and a drying cabinet by Yaldiz et al. Twenty-two experiments were performed in order to examine the effect of drying air temperature and velocity on thin layer drying of Sultana grapes. Eight different thin layer mathematical drying models were compared according to their coefficient of determination to estimate solar drying curves and the results showed that a two-term drying model could satisfactorily describe the solar drying curve of Sultana grapes with a correlation coefficient (r) of 0.979 [141].

5.3. Onion dryers

An infrared dryer was developed and infrared radiation thin layer drying of onion slices was carried out at infrared power levels of 300 W, 400 W and 500 W, air temperatures of 35 °C, 40 °C and 45 °C and air velocities of 1.0 m/s, 1.25 m/s and 1.5 m/s by Sharma et al. The results indicated that the drying rate increased with increase in infrared power at a given air temperature and velocity thus reducing the drying time and the drying time increased with increase in air velocity at a given infrared power and air temperature because of the increased cooling effect at the surface of the product. Eight available moisture-ratio models were fitted to the drying data, of which Page's model had a higher correlation coefficient and low chi-square value and thus predicted drying behavior of the onion slices more accurately [142]. Open sun and greenhouse drying of onion flakes was performed by Kumar and Tiwari, to study the effect of mass on convective mass transfer coefficient. The data obtained from experimentation under open sun and greenhouse

conditions was used to determine values of the constant '*C*' and exponent '*n*' by regression analysis and, consequently, convective mass transfer coefficient and it was observed that there is a significant effect of mass on convective mass transfer coefficient for open as well as greenhouse drying. It was also observed that the rate of moisture evaporation in case of greenhouse drying is more than that in open sun drying during the off-sunshine hours due to the stored energy inside the greenhouse [143]. A solar-assisted forced convection dryer was developed by Sarsavadia to study the effect of airflow rate (2.43 kg/min, 5.25 kg/min, 8.09 kg/min), air temperature (55 °C, 65 °C, 75 °C), and fraction of air recycled (up to 90%) on the total energy requirement of drying of onion slices. For drying of onion slices from initial moisture content of about 86% (wet basis) to final moisture content of about 7% (wet basis), the energy required per unit mass of water removed without using recirculation of air was found to be between 23.548 MJ/kg and 62.117 MJ/kg water; the percent energy contribution by the solar air heater, electrical heater, and blower was found between 24.5% and 44.5%, 40.2% and 66.9%, and 8.6% and 16.3%, respectively; the maximum saving in total energy up to 70.7% was achieved by recycling of the exhaust air; the energy required per unit mass of water removed was found between 12.040 MJ/kg and 38.777 MJ/kg water and the percent energy contribution by the solar air heater, auxiliary heater, and blower was found between 22.4% and 40.9%, 33.6% and 62.6%, and 11.2% and 37.2%, respectively [144].

5.4. Potato dryers

A method based on energy balance considering the effects of heat capacity of the food product, radiative heat transfer from food product to the drying chamber and solar radiation absorbed in the product during drying was proposed by Tripathy and Kumar for determination of convective heat transfer coefficient, h_c, with a natural convection mixed-mode solar dryer being used for performing the experiments on potato cylinders and slices of same thickness of 0.01 m with respective length and diameter of 0.05 m. The investigation indicated that the cylindrical samples exhibit higher values of h_c and faster drying rate compared to those of slices, as expected. Results of energy analysis revealed that for both the sample geometries, decreasing product moisture content during drying resulted in significant reduction in specific energy consumption and for almost similar drying conditions, a considerable amount of reduction in specific energy consumption is achieved for cylinders, as expected [145]. A methodology for the determination of temperature dependent drying parameters namely drying constant and lag factor from the experimental drying kinetic curves of food product was proposed by Tripathy and Kumar, using a laboratory scale mixed-mode solar dryer consisting of an inclined flat-plate solar collector connected in series to a drying chamber glazed at the top to perform natural convection drying experiments with potato cylinders of length 0.05 m and diameter 0.01 m and slices of diameter 0.05 m and thickness 0.01 m. The thin-layer drying equation describing the drying behavior of food products is derived from Fick's law of diffusion and the analysis revealed that both drying constant and lag factor increase with sample temperature, as expected [146]. The application of artificial neural networks (ANN) for prediction of temperature variation of food products during solar drying was investigated by Tripathy and Kumar, considering the important climatic variables namely solar radiation intensity and ambient air temperature as the input parameters for ANN modeling. Experimental data on potato cylinders and slices obtained with mixed mode solar dryer for 9 typical days of different months of the year were used for training and testing the neural network and a methodology was proposed for development of optimal neural network. Results of analysis revealed that the network with 4 neurons and logsig transfer function and trainrp back propagation algorithm is the most appropriate approach for both potato cylinders and slices based on minimum measures of error [147].

5.5. Sweet potatoes dryers

Six varieties of sweet potatoes (Santana, Santea, Marfona, Diamant, Koncord, Renjer) were chosen as drying material and dried using a pilot-scale tray dryer, with and without air circulation, and a fluidized bed dryer. The experiments were performed with and without blanching by Hatamipour et al., to study the changes in structure and color of the six varieties of potatoes. Results indicated that temperature has no significant effect on shrinkage, but blanching time and air circulation has significant effect on shrinkage as well as on the appearance of dried product. The quality and appearance of all varieties was found to be very good in fluidized bed dryer and blanching was effective in improving the color of all dried varieties [148]. Different drying treatments, cross flow, greenhouse solar and open air-sun were applied to an American orange-fleshed sweet potato variety by Bechoff et al. and found that *Trans*-β-carotene losses in flour made from dried chips varied between 16% and 34% in all treatments and hot air cross flow drying retained significantly more pro-vitamin A than sun drying[149]. An indirect solar dryer was used by Diamante and Munro to study the drying of sweet potato slices and a mathematical model for solar drying of sweet potato slices was derived based on the simplified form of the Fick's diffusion equation. It was observed that the solar drying rates of sweet potato slices were affected by the fluctuating chamber temperature over the drying period and the solar drying rate curves exhibited a constant rate period and one linear falling rate period and the mean effective drying chamber temperature and sample thickness were the main factors that affected the solar drying process for sweet potato slices [150].

5.6. Other vegetables drying

The thermal behavior of OSD of green chillies, green peas, white gram (kabuli chana), onions, potatoes, and cauliflowers were studied by Jain and Tiwari. The heat transfer analysis which is mainly dependent on the rate of moisture transfer was made during the drying process. A mathematical model was developed to predict the crop temperature, rate of moisture removal and air temperature for a steady state condition and the rate of moisture transfer for potato slices and cauliflower was found to be significantly higher than that in other crops [151]. An indirect type natural convection locally made solar dryer, consisting of a flat-plate solar air heater connected to a drying chamber, was investigated experimentally and theoretically by El-Sabaii et al., with the drying of fruits and vegetables such as seedless grapes, figs, green peas, tomatoes and onions. Linear correlations between drying constants k and drying product temperature T_{dp} were found to satisfactorily describe the drying curves of the materials under study. The characteristics constants c and n of Henderson's equation were determined for the selected crops using the experimentally measured relative humidity of the drying air and a simple mathematical model was presented for the drying chamber based on the energy and mass balance equations and employing the proposed correlations for k as well as the values of the constants c and n [152]. A study of convective mass transfer coefficient and rate of moisture removal from cabbage and peas for open sun drying and inside greenhouse drying was performed as a function of climatic parameters by Jain and Tiwari. The convective mass transfer coefficient was found to be lower for drying inside the greenhouse with natural mode as compared to open sun drying and its value was doubled under the forced mode inside the greenhouse drying compared to natural convection in the initial stage of drying [153]. Jain and Tiwari presented the mathematical models to study the thermal behavior of crops

(cabbage and peas) for open sun drying (natural convection) and inside the greenhouse under both natural and forced convection. The predictions of crop temperature, greenhouse room air temperature and rate of moisture evaporation (crop mass during drying) were computed using Matlab software on the basis of solar intensity and ambient temperature and the models were experimentally validated [154]. An experimental study was performed by Sacilik to determine the drying characteristics of hull-less seed pumpkin using hot air, solar tunnel and open sun drying methods. For the hot air drying, the test samples were dried in a laboratory scale hot air dryer at a constant air velocity of 0.8 m/s and air temperature in the range of 40–60 °C and for solar drying experiments, a solar tunnel dryer was constructed at a low cost with locally obtainable materials. The experimental drying data of hull-less seed pumpkin were used to fit the Page, Henderson and Pabis, logarithmic and two-term models, and drying rate constants and coefficients of models tested were determined by non-linear regression analysis. It was found that among the various models tested to interpret the drying behavior of hull-less seed pumpkin, one was selected which presented best statistical indicators [155]. A forced convective, flat-plate, solar heat collector was developed and tested for drying cauliflower by Kadam and Samuel. Solar time (14:363 h), standard time (+5:30 h), solar declination angle (−7.15°), total sunshine duration (11:48 h) and solar heat collector thermal efficiency were calculated using solar collector theory and the average mid-day thermal efficiency was around 16.5% and the peaks out of this average were due to the inertia effect that keeps the collector temperature almost constant for some minutes when the radiation falls. A linear correlation between the temperature difference from ambient ($T - T_a$) and the radiation I, as well as inlet and outlet air temperature and RH were also obtained [156]. A solar drying system designed on the principles of convective heat flow was constructed from local materials (wood, metals and glass sheets) and used to dry food crops(cassava, pepper, okra, groundnuts, etc.) by Akwasi Ayensu and the low-temperature drying system ensured the viability of the seeds for planting. The drying process took place in two phases: constant rate and falling rate periods, and the drying equation was solved to predict the total drying time and the mechanisms for the dehydration were the removal of unbound “free” water in the cell cavities and of “bound” water (water films) trapped within cells or chemically bound with solids as water of crystallization [157]. A solar tunnel dryer was optimized for drying chilli in Bangladesh by Hossain et al. The simulation model was combined with the economic model of the solar tunnel dryer and adaptive pattern search was used to find the optimum dimensions of the collector and the drying unit. Two optimum designs were obtained. For design-1, both collector and drying unit were 14.0 m long and 1.9 m wide and for design-2, both collector and drying unit were 13.0 m long and 2.0 m wide. The capacity of optimum mode dryers was found to be higher than the basic mode dryer and achieved a cost saving of 15.9%. The payback period of the basic mode dryer is 4 years and optimum mode dryer is about 3 years. Sensitivity analysis showed that the design geometry is sensitive to costs of major construction materials of the collector and air temperature in the dryer [158]. A mixed mode type forced convection solar tunnel dryer, consisting of transparent plastic covered flat-plate collector and a drying tunnel connected in series to supply hot air directly into the drying tunnel using two fans operated by a photovoltaic module, was used to dry hot red and green chillies under the tropical weather conditions of Bangladesh. The use of a solar tunnel dryer and blanching of sample led to a considerable reduction in drying time and dried products of better quality in terms of colour and pungency in comparison to products dried under the sun and hence the solar tunnel dryer and blanching of chilli were recommended for drying of both red and green chillies [159]. Chauhan et al. studied the drying characteristics of coriander in a stationary 0.5 tonne/batch capacity deep-bed dryer coupled to a solar air heater and a rock bed storage unit to receive hot air during sunshine and off-sunshine hours, respectively. The theoretical investigation was made by writing the energy and mass balance equations for different components of the dryer-cum-air-heater-cum-storage and by adopting a finite difference approach for simulation and the results revealed that for reducing the moisture content from 28.2% (db) to 11.4% (db) the solar air heater takes 27 cumulative sunshine hours, i.e. about 3 sunshine days, whereas the solar air heater and the rock bed storage combined take 31 cumulative hours, i.e. about 2 days and 2 nights at an air flow velocity of 250 kg/hm^2 [160]. A direct type natural convection solar cum biomass dryer was developed and its performance for the drying of turmeric rhizomes was evaluated by Prasad et al. Dried turmeric rhizomes obtained under solar biomass (hybrid) drying by two different treatments viz., water boiling and slicing were similar in quality with respect to physical appearances like color, texture, etc. but there is significant variation in volatile oil. The quantitative analysis showed that the traditional drying i.e., open sun drying took 11 days to dry the rhizomes while solar biomass dryer took only 1.5 days and produced better quality [161]. In order to study the drying of red pepper in open sun and greenhouse conditions drying experiments at constant laboratory conditions and at varying outdoor conditions were carried out by Kooli et al. Laboratory drying experiments were undertaken, inside a wind tunnel where solar radiation was simulated by a 1000 W lamp, for different external parameters (incident radiation, ambient temperature and air velocity) and the effect of drying parameters on moisture content and drying time were determined. A simple drying model of red pepper related to water evaporation process was developed and verified and it was found that the laboratory model overestimates the drying process under time varying conditions and a correction factor was then introduced in the formulation of the model to adjust these predictions [162]. An experimental study was performed by Akpinar and Bicer, to determine the thin layer drying characteristics in a solar dryer with forced convection and under open sun with natural convection of long green pepper, using an indirect forced convection solar dryer consisting of a solar air collector and drying cabinet. The drying process took place in the falling rate period and the drying data were fitted to 13 different mathematical models. Among the models, the logarithmic model for forced solar drying and the Midilli and Kucuk model for natural sun drying were found best to explain the thin layer drying behaviour of long green peppers [163]. McDoom et al. made investigations on the moisture content reduction of coconut and cocoa using a scaled-down dryer of the type found on coconut estates in Trinidad. The energy used in continuous vent mode, intermittent vent mode and partial recycle mode were compared and an energy saving of 29 to 31% was realized by re-circulating the hot air and varying the degree of venting. It was found that this saving could also be effected on the estates with suitable modification of the dryers used there [164]. Experiments to investigate the effectiveness of solar-heat collectors used in conjunction with electric or oil-burning heaters for providing heated air for drying coffee were described by Allan Phillips. A solar-heat collector was constructed as part of the roof of a coffee-processing building in an experimental installation, which was operated during two harvesting seasons, and it was observed that electricity costs were reduced by amounts up to 66 percent as compared to other installations that did not incorporate solar-heat collectors. Recommendations for the design of coffee drying facilities were also included [165]. The feasibility of solar and combined solar-natural air drying of rapeseed was evaluated using computer simulations by Patil and Ward. Simulations have been carried out for the three harvesting dates of 10 and 25 February and 10 March and the five moisture contents of 25%, 22%, 20%, 18%, and 14% (db) using an airflow rate of 180 m^3 (h m^2)$^{-1}$ and it was found that both total and actual drying times are increased with increasing

depth and initial moisture content. The study of drying parameter profiles showed that a faster and more complete drying is observed using solar-natural air drying, which was also reflected in the width of drying front being greater when solar-natural drying than when using solar drying alone. The solar-natural air drying regime appeared to be superior to that of solar drying alone with respect to the required total drying time and in achieving complete drying within the safe storage time, with a saving of actual drying hours [166]. A solar heated dryer was developed by Muller et al., taking a plastic film greenhouse as superstructure to lower the initial costs, consisting of a black absorber tissue, which is placed between the transparent cover of the greenhouse and an insulating air-bubble foil. A prototype was tested in Yugoslavia, drying mint, sage and hops. Compared to conventionally dried crude drugs, the percentage of active ingredients was up to 40% higher and the low investment and operating cost and the high quality of the crude drugs permit the solar dryer to be used in agriculture [167]. A bin-type solar dryer for drying herbs and spices using hot air from roof-integrated solar collectors was developed by Janjai and Tung. To investigate its performance, the dryer was used to dry four batches of rosella flowers and three batches of lemon-grasses during the year 2002–2003. The products being dried in the dryer were completely protected from rains and insects and the dried products were of high quality and the solar air heater was found to have an average daily efficiency of 35% and it performed well both as a solar collector and a roof of a farmhouse [168]. Janjai et al. presented the experimental performance of solar drying of rosella flower and chilli using roof-integrated solar dryer and also the modeling of the roof-integrated solar dryer for drying of chili. Field-level tests for deep bed drying of rosella flower and chili demonstrated that drying in the roof-integrated solar dryer resulted in significant reduction in drying time compared to the traditional sun drying method and the dry product is a quality dry product compared to the quality products in the markets. Economical investigations revealed that the payback period of the roof-integrated solar dryer is about 5 years [169]. Rosemary leaves (*Rosmarinus officinalis* L., Lamiaceae) were dried by using sun, oven (50 °C) and microwave oven (700 W, 2450 MHz) drying methods by Arslan and Ozcan to study their characteristics. Microwave oven drying shortened the drying time more than 99% when compared to the sun and oven drying methods. The mineral content of oven dried rosemary leaves (K, Ca, Na, Mg and P) was higher than that of the sun and microwave dried samples and the logarithmic and Midilli and Küçük models were shown to give a good fit to the sun and oven drying. The Page, Modified Page and Midilli and Küçük models showed a better fit to the experimental microwave oven drying data of rosemary leaves [170]. Kumar and Tiwari developed a thermal model so as to predict the jaggery temperature, the greenhouse air temperature and the moisture evaporated (jaggery mass during drying), during the drying of jaggery under natural convection conditions. A computer program was developed in MATLAB software so as to calculate the jaggery temperature, the greenhouse air temperature and the moisture evaporated was also used to predict the thermal performance of the greenhouse on the basis of solar intensity and ambient temperature and the software developed was experimentally validated. It was shown that the analytical and experimental results for jaggery drying are in good agreement [171]. A mathematical model of direct sun and solar drying of some fermented dairy products (Kishk) was developed by Bahnasawy and Shenana, the solar radiation, heat convection, heat gained or lost from the dryer bin wall and the latent heat of moisture evaporation being the main components of the equations describing the drying system. The model was able to predict the drying temperatures at a wide range of relative humidity values and had the capability to predict the moisture loss from the product at wide ranges of RH values, temperatures and air velocities. The model showed the dramatic effect of the air velocity on increasing the moisture loss at the beginning of the drying process and became constant, which leads to a recommendation that it is better to use low temperature with forced air at the beginning of drying and in the next stages, high temperature without forced air should be used [172]. Nijmeh et al. investigated the potential of using two solar dryers, namely a radiative–convective type and a solar boiler dryer, manufactured from locally available materials under Jordanian climatic conditions for drying food wastes for utilization as animal feed. Tests were also conducted to investigate the nutritional values of the dried products and their suitability as animal feed and it was found from tests that the solar boiler dryer is more efficient than the radiative–convective dryer for producing animal feed in terms of both quality and quantity. The nutritional values of the end products from the dryers were found to be within the internationally recommended values used for feeding chickens [173]. Performances of a new designed Double-pass solar drier (DPSD) were compared with those of a typical cabinet drier (CD) and a traditional open-air sun drying for drying of red chilli in central Vietnam. Banout et al. stated that the Double-pass solar drier was found to be technically suitable and economically viable for drying of red chillies in central Vietnam [174]. Maiti et al. reported the design and development of an indirect, natural convection batch-type solar dryer fitted with North-South reflectors [175]. The desired extent of drying of 'papad' – a popular Indian wafer – could be achieved within 5 h in this static dryer having 1.8 m^2 area of the collector and computed loading capacity of 3.46 kg. A review on advanced of solar assisted chemical heat pump dryer for agriculture produce was presented by Fadhel et al. [176]. Description of chemical heat pump types and the overview of chemical heat pump dryer are also discussed. The combination of chemical heat pump and solar technology gives extra efficiency in utilizing energy.

6. Conclusion

The best alternative to overcome the disadvantages of traditional open sun drying and the use of fossil fuels, is the development of solar crop dryers. In addition to mitigation of fossil fuel use, the quality of the dried crops is also higher and the loss of dried products is considerably reduced. The state of art technologies of solar dryers reviewed were as follows:

- The status of solar dryers with respect to the developing countries was reviewed.
- The design, development and performance evaluation of various types of solar dryers were reviewed.
- Various types of dryers like natural convection and forced convection dryers, direct and indirect type dryers, integral dryers, greenhouse dryers, cabinet dryers, tunnel dryers, mixed mode dryers were reviewed with respect to their design and performance.
- Special attention was given to the solar drying technologies which facilitate the drying of crops in the off-sunshine hours. A desiccant based solar drying system was one such technology briefly discussed.
- Solar dryers designed specifically for a particular crop like grain dryers, grapes dryer, onion dryers, potato dryers, etc. were reviewed with their design, performance evaluation and the results of simulation of the systems.

References

[1] Lof GOG. Recent investigations in the use of solar energy for the drying of solids. Solar Energy 1962;6(4):122–8.
[2] Esper A, Muhlbauer W. Solar drying –an effective means of food preservation. Renew Energy 1998;15(1–4):95–100.
[3] Muhlbauer W. Present status of solar crop drying. Energy Agric 1986;5(2):121–37.

[4] Purohit P, Kumar A, Kandpal TC. Solar drying vs. open sun drying; a framework for financial evaluation. Solar Energy 2006;80(12):1568–79.
[5] Ekechukwu OV. Review of solar energy drying I: an overview of drying principles and theory. Energy Convers Manage 1999;40(6):593–613.
[6] Ekechukwu OV, Norton B. Review of solar energy drying II: an overview of drying technology. Energy Convers Manage 1999;40(6):615–55.
[7] Ekechukwu OV, Norton B. Review of solar energy drying III: low temperature air-heating solar collectors for crop drying applications. Energy Convers Manage 1999;40(6):657–67.
[8] Fudholi A, Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY. Review of solar dryers for agricultural and marine products. Renew Sustain Energy Rev 2010;14(1):1–30.
[9] Chua KJ, Chou SK. Low-cost drying methods for developing countries. Trends Food Sci Technol 2003;14(12):519–28.
[10] Sharma VK, Colangelo A, Spagna G, Pistocchi F. Preliminary economic appraisal of solar air heating system used for drying of agricultural products. Energy Convers Manage 1994;35(2):105–10.
[11] Saif-Ul-Rehman M. Prospects and limitations of solar energy utilization in developing countries. Solar Energy 1967;11(2):98–108.
[12] Ong KS. Solar dryers in the Asia-Pacific region. Renew Energy 1999;16(1–4):779–84.
[13] Vecchia D, Formisano G, Rosseli V, Ruggi D. Possibilities for the application of solar energy in the European community agriculture. Solar Energy 1981;26(6):479–89.
[14] Wisniewski G. Market development of solar crops drying technologies in Poland and Europe. Renew Energy 1999;16(1–4):1278–83.
[15] Arinze EA, Sokhansanj S, Schoenau GJ. Simulation of natural and solar-heated air hay drying systems. Comput Electron Agric 1993;8(4):325–45.
[16] Kumar A, Kandpal TC. Solar drying and CO_2 emission mitigation: potential for selected cash crops in India. Solar Energy 2005;78(2):321–9.
[17] Bansal NK. Solar energy heater application in India. Renew Energy 1999;16(1–4):618–23.
[18] Joshi CB, Pradhan BD, Pathak TP. Application of solar drying systems in Nepal. World Renewable Energy congress VI; 2000. p. 2237–2240.
[19] Lhendup T. Technical and financial feasibility of a solar dryer in Bhutan. Energy Sustain Dev 2005;9(4):17–24.
[20] Sopontonnarit S. Solar drying in Thailand. Energy Sustain Dev 1995;2(2):19–25.
[21] Roman F, Nagle M, Leis H, Janjai S, Mahayothee B, Haewsungcharoen M, et al. Potential of roof-integrated solar collectors for preheating air at drying facilities in Northern Thailand. Renew Energy 2009;34(7):1661–7.
[22] Oztek S, Bacet ncel k A, Soysal Y. Crop drying programme in Turkey. Renew Energy 1999;16(1–4):789–94.
[23] Salihoglu NK, Pinarli V, Salihoglu G. Solar drying in sludge management in Turkey. Renew Energy 2007;32(10):1661–75.
[24] Headley OSC. Solar thermal applications in the West Indies. Renew Energy 1998;15(1–4):257–63.
[25] Headley OSC. Solar crop drying in the West Indies. World Renewable Energy congress VI; 2000. p. 934–939.
[26] Lawrence SA, Pole A, Tiwari GN. Performance of a solar crop dryer under PNG climatic conditions. Energy Convers Manage 1990;30(4):333–42.
[27] Zahed AH, Bashir MD, Khalifa AMA. A perspective of solar drying of crops – a country profile. Solar Wind Technol 1988;5(3):249–62.
[28] Cheapok C, Pornnareay P. Introducing solar drying in a developing country: the case of Cambodia. World Renewable Energy congress VI; 2000. p. 2198–2201.
[29] Ben Mabrouk S, Belghith A. Development of the solar crop dryers in Tunisia. World Renewable Energy congress VI; 2000. p. 2206–2211.
[30] Roman R. Solar drying in northern Chile. Solar Wind Technol 1984;1(1):49–58.
[31] Sharma A, Chen CR, Lan NV. Solar energy drying systems: a review. Renew Sustain Energy Rev 2009;13(6–7):1185–210.
[32] Sodha MS, Chandra R. Solar drying systems and their testing procedures: a review. Energy Convers Manage 1994;35(3):219–67.
[33] Augustus Leon M, Kumar S, Bhattacharya SC. A comprehensive procedure for performance evaluation of solar food dryers. Renew Sustain Energy Rev 2002;6(4):367–93.
[34] Ramana Murthy MV. A review of new technologies, models and experimental investigations of solar driers. Renew Sustain Energy Rev 2009;13(4): 835–44.
[35] Arata A, Sharma VK. Performance evaluation of solar assisted dryers for low-temperature drying applications I: plants description. Renew Energy 1991;1(5–6):729–35.
[36] Sharma VK, Colangelo A, Spagna G. Experimental investigation of different solar dryers suitable for fruit and vegetable drying. Renew Energy 1995;6(4):413–24.
[37] Chandra R, Sodha MS. Testing procedures for solar air heaters: a review. Renew Sustain Energy Rev 1991;32(1):11–33.
[38] Henricksson R, Gustafsson G. Use of solar collectors for drying agricultural crops and for heating farm buildings. Energy Agric 1986;5(2):139–50.
[39] Koyuncu T. Performance of various design of solar air heaters for crop drying applications. Renew Energy 2006;31(7):1073–88.
[40] Ayensu A, Asiedu Bondzie V. Solar drying with convective self-flow and energy storage. Solar Wind Technol 1986;3(4):273–9.
[41] Othman MYH, Sopian K, Yatim B, Daud WRW. Development of advanced solar drying systems. Renew Energy 2006;31(5):703–9.
[42] Womac AR, Tompkins FD, DeBusk KE. Evaluation of solar air heaters for crop drying. Energy Agric 1985;4:147–57.
[43] Garg HP, Mahajan RB, Sharma VK, Acharya HS. Design and development of a simple solar dehydrator for crop drying. Energy Convers Manage 1984;24(3):229–35.
[44] Tiris C, Tiris M, Dincer I. Investigation of the thermal efficiencies of a solar dryer. Energy Convers Manage 1995;36(3):205–12.
[45] Tiwari GN, Bhatia PS, Singh AK, Sutar Roy F. Design parameters of a shallow bed solar crop dryer with reflector. Energy Convers Manage 1994;35(6):535–42.
[46] Pitt RE. Stochastic theory of forage drying as related to pan evaporation. Agric Forest Meteor 1984;32(3–4):197–215.
[47] Chemkhi S, Zagrouba F, Bellagi A. Drying of agricultural crops by solar energy. Desalination 2004;168:101–9.
[48] Tripathy PP, Kumar S. A methodology for determination of temperature dependent mass transfer coefficients from drying kinetics: application to solar drying. J Food Eng 2009;90(2):212–8.
[49] Anwar SI, Tiwari GN. Evaluation of convective heat transfer coefficient in crop drying under open sun drying conditions. Energy Convers Manage 2001;42(5):627–37.
[50] Anwar SI, Tiwari GN. Convective heat transfer coefficient of crops in forced convection drying – an experimental study. Energy Convers Manage 2001;42(14):1687–98.
[51] Sharma VK, Sharma S, Ray RA, Garg HP. Design and performance studies of a solar dryer suitable for rural applications. Energy Convers Manage 1986;26(1):111–9.
[52] Jain D. Modeling the performance of the reversed absorber with packed bed thermal storage natural convection solar crop dryer. J Food Eng 2007;78(2):637–47.
[53] Bena B, Fuller RJ. Natural convection solar dryer with biomass back-up heater. Solar Energy 2002;72(1):75–83.
[54] Pangavhane DR, Sawhney RL, Sarsavadia PN. Design, development and performance testing of a new natural convection solar dryer. Energy 2002;27(6):579–90.
[55] Gbaha P, Yobouet Andoh H, Kouassi Saraka J, Kamenan Koua B, Toure S. Experimental investigation of a solar dryer with natural convective heat flow. Renew Energy 2007;32(11):1817–29.
[56] Huang BK, Toksoy M. Design and analysis of greenhouse solar systems in agricultural production. Energy Agric 1983;2:115–36.
[57] Janjai S, Lamlert N, Intawee P, Mahayothee B, Bala BK, Nagle M, et al. Experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. Solar Energy 2009;83(9): 1550–65.
[58] Jain D. Modeling the performance of greenhouse with packed bed thermal storage on crop drying application. J Food Eng 2005;71(2):170–8.
[59] Sethi VP, Arora S. Improvement in greenhouse solar drying using inclined north wall reflection. Solar Energy 2009;83(9):1472–84.
[60] Sharma VK, Colangelo A, Spagna G. Experimental performance of an indirect type solar fruit and vegetable dryer. Energy Convers Manage 1993;34(4):293–308.
[61] Boughali S, Benmoussa H, Bouchekima B, Mennouche D, Bouguettaia H, Bechki D. Crop drying by indirect active hybrid solar – electrical dryer in the eastern Algerian Septentrional Sahara. Solar Energy 2009;83(12): 2223–32.
[62] El-Sebaii AA, Aboul-Enein S, Ramadan MRI, El-Gohary HG. Experimental investigation of an indirect type natural convection solar dryer. Energy Convers Manage 2002;43(16):2251–66.
[63] Celma AR, Cuadros F. Energy and exergy analyses of OMW solar drying process. Renew Energy 2009;34(3):660–6.
[64] Madhlopa A, Ngwalo G. Solar dryer with thermal storage and biomass-backup heater. Solar Energy 2007;81(4):449–62.
[65] Bassey MW, Oosthuizen PH, Sarr J. Using heated chimneys and reduced collector air gap height to improve the performance of indirect passive solar dryers. Renew Energy 1994;4(2):169–78.
[66] Sharma VK, Colangelo A, Spagna G. Investigation of an indirect type multi-shelf solar fruit and vegetable dryer. Renew Energy 1992;2(6):577–86.
[67] Singh S, Singh PP, Dhaliwal SS. Multi-shelf portable solar dryer. Renew Energy 2004;29(5):753–65.
[68] Singh PP, Singh S, Dhaliwal SS. Multi-shelf domestic solar dryer. Energy Convers Manage 2006;47(13–14):1799–815.
[69] Al-Juamily KEJ, Khalifa AJN, Yassen TA. Testing of the performance of a fruit and vegetable solar drying system in Iraq. Desalination 2007;209(1–3):163–70.
[70] Dutta G, Garg HP, Ray RA, Prakash J. Performance prediction of a cabinet-type solar drier. Solar Wind Technol 1988;5(3):289–92.
[71] Sharma S, Sharma VK, Jha R, Ray RA. Evaluation of the performance of a cabinet type solar dryer. Energy Convers Manage 1990;30(2):75–80.
[72] Sreekumar A, Manikantan PE, Vijayakumar KP. Performance of indirect solar cabinet dryer. Energy Convers Manage 2008;49(6):1388–95.
[73] Goyal RK, Tiwari GN. Performance of a reverse flat plate absorber cabinet dryer: a new concept. Energy Convers Manage 1999;40(4):385–92.
[74] Garg HP, Kumar R. Studies on semi-cylindrical solar tunnel dryers: thermal performance of collector. Appl Therm Eng 2000;20(2):115–31.
[75] Amir EJ, Grandegger K, Esper A, Sumarsono M, Djaya C, Muhlbauer W. Development of a multi-purpose solar tunnel dryer for use in humid tropics. Renew Energy 1991;1(2):167–76.

[76] Ekechukwu OV, Norton B. Experimental studies of integral-type natural-circulation solar -energy tropical crop dryers. Energy Convers Manage 1997;38(14):1483–500.
[77] Ekechukwu OV, Norton B. Effects of seasonal weather variations on the measured performance of a natural-circulation solar -energy tropical crop dryer. Energy Convers Manage 1998;39(12):1265–76.
[78] Onyegegbu SO, Morhenne J, Norton B. Second law optimization of integral type natural circulation solar energy crop dryers. Energy Convers Manage 1994;35(11):973–83.
[79] Sharma VK, Rizzi G, Garg HP. Design and development of an augmented integrated solar collector with rock storage system for heating applications. Energy Convers Manage 1991;31(4):369–77.
[80] Forson FK, Nazha MAA, Rajakaruna H. Modeling and experimental studies on a mixed-mode natural convection solar crop -dryer. Solar Energy 2007;81(3):346–57.
[81] Forson FK, Nazha MAA, Akuffo FO, Rajakaruna H. Design of mixed-mode natural convection solar crop dryers: Application of principles and rules of thumb. Renew Energy 2007;32(14):2306–19.
[82] Ferreira AG, Cristina VM, Marcio FBC, Ramon MV. Technical feasibility assessment of a solar chimney for food drying. Solar Energy 2008;82(3):198–205.
[83] Afriyie JK, Nazha MAA, Rajakaruna H, Forson FK. Experimental investigations of a chimney-dependent solar crop dryer. Renew Energy 2009;34(1): 217–22.
[84] Das SK, Kumar Y. Design and performance of a solar dryer with vertical collector chimney suitable for rural application. Energy Convers Manage 1989;29(2):129–35.
[85] Othman MYH, Yatim B, Hafidz RM. Preliminary results of a V-groove back-pass solar collector. Renew Energy 1996;9(1–4):622–5.
[86] Sopian K, Alghoul MA, Alfegi EM, Sulaiman MY, Musa EA. Evaluation of thermal efficiency of double-pass solar collector with porous–nonporous media. Renew Energy 2009;34(3):640–5.
[87] Jain D, Jain RK. Performance evaluation of an inclined multi-pass solar air heater with in-built thermal storage on deep-bed drying application. J Food Eng 2004;65(4):497–509.
[88] Jain D. Modeling the system performance of multi-tray crop drying using an inclined multi-pass solar air heater with in-built thermal storage. J Food Eng 2005;71(1):44–54.
[89] Esper A, Lutz K, Muhlbauer W. Development and testing of plastic film solar air heaters. Solar Wind Technol 1989;6(3):189–95.
[90] Ahmad NT. Agricultural solar air collector made from low cost plastic packing film. Renew Energy 2001;23(3–4):663–71.
[91] Saleh A, Badran I. Modeling and experimental studies on a domestic solar dryer. Renew Energy 2009;34(10):2239–45.
[92] Tiris C, Tiris M, Dincer I. Experiments on a new small-scale solar dryer. Appl Therm Eng 1996;16(2):183–7.
[93] Khanna ML, Singh NM. Industrial solar drying. Solar Energy 1967;11(2):87–9.
[94] Lutz K, Muhlbauer W, Muller J, Reisinger G. Development of a multi-purpose solar crop dryer for arid zones. Solar Wind Technol 1987;4(4):417–24.
[95] Taylor KJ, Weir AD. Simulation of a solar timber drier. Solar Energy 1985;34(3):249–55.
[96] Luna D, Nadeau JP, Jannot Y. Solar timber kilns: state of the art and foreseeable developments. Renew Sustain Energy Rev 2009;13(6–7):1446–55.
[97] Aboul-Enein S, El-Sebaii AA, Ramadan MRI, El-Gohary HG. Parametric study of a solar air heater with and without thermal storage for solar drying applications. Renew Energy 2000;21(3–4):505–22.
[98] Enibe SO. Performance of a natural circulation solar air heating system with phase change material energy storage. Renew Energy 2002;27(1):69–86.
[99] Tiwari GN, Bhatia PS, Singh AK, Goyal RK. Analytical studies of crop drying cum water heating system. Energy Convers Manage 1997;38(8):751–9.
[100] Akyurt M, Selcuk MK. A solar drier supplemented with auxiliary heating systems for continuous operation. Solar Energy 1973;14(3):313–20.
[101] Thoruwa TFN, Johnstone CM, Grant AD, Smith JE. Novel, low cost $CaCl_2$ based desiccants for solar crop drying applications. Renew Energy 2000;19(4):513–20.
[102] Shanmugam V, Natarajan E. Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror. Appl Therm Eng 2007;27(8–9):1543–51.
[103] Shanmugam V, Natarajan E. Experimental investigation of forced convection and desiccant integrated solar dryer. Renew Energy 2006;31(8):1239–51.
[104] Mahmouda KG, Ball HD. Solar desiccant systems for grain drying. Energy Convers Manage 1991;31(6):595–8.
[105] Hodali R, Bougard J. Integration of a desiccant unit in crops solar drying installation: optimization by numerical simulation. Energy Convers Manage 2001;42(13):1543–58.
[106] Thoruwa TFN, Smith JE, Grant AD, Johnstone CM. Developments in solar drying using forced ventilation and solar regenerated desiccant materials. Renew Energy 1996;9(1–4):686–9.
[107] Punlek C, Pairintra R, Chindaraksa S, Maneewan S. Simulation design and evaluation of hybrid PV/T assisted desiccant integrated HA-IR drying system (HPIRD). Food Bioprod Process 2009;87(2):77–86.
[108] Mumba J. Design and development of a solar grain dryer incorporating photovoltaic powered air circulation. Energy Convers Manage 1996;37(5):615–21.
[109] Radajewski W, Jolly P, Abawi GY. Optimization of solar grain drying in a continuous flow dryer. J Agric Eng Res 1987;38(2):127–44.
[110] Best R, Soto W, Pilatowsky I, Gutierrez LJ. Evaluation of a rice drying system using a solar assisted heat pump. Renew Energy 1994;5(1–4):465–8.
[111] Basunia MA, Abe T. Thin-layer solar drying characteristics of rough rice under natural convection. J Food Eng 2001;47(4):295–301.
[112] Zaman MA, Bala BK. Thin layer solar drying of rough rice. Solar Energy 1989;42(2):167–71.
[113] Bala BK, Wood JL. Simulation of the indirect natural convection solar drying of rough rice. Solar Energy 1994;53(3):259–66.
[114] Janjai S, Esper A, Muhlbauer W. A procedure for determining the optimum collector area for a solar paddy drying system. Renew Energy 1994;4(4):409–16.
[115] Zomorodian A, Zare D, GHasemkhani H. Optimization and evaluation of a semi-continuous solar dryer for cereals (Rice, etc.). Desalination 2007;209(1–3):129–35.
[116] Simate IN. Optimization of mixed-mode and indirect-mode natural convection solar dryers. Rnewable Energy 2003;28(3):435–53.
[117] Tiwari GN, Singh AK, Bhatia PS. Experimental simulation of a grain drying system. Energy Convers Manage 1994;35(5):453–8.
[118] Fraser BM, Muir WE. Energy consumptions predicted for drying grain with ambient and solar -heated air in Canada. J Agric Eng Res 1980;25(3): 325–31.
[119] Tayeb AM. Modern solar grain dryer. Solar Wind Technol 1986;3(3): 211–4.
[120] Roa G, Macedo IC. Grain drying in stationary bins with solar heated air. Solar Energy 1976;18(5):445–9.
[121] Koua KB, Fassinou WF, Gbaha P, Toure S. Mathematical modelling of the thin layer solar drying of banana, mango and cassava. Energy 2009;34(10):1594–602.
[122] Aktas M, Ceylan I, Yilmaz S. Determination of drying characteristics of apples in a heat pump and solar dryer. Desalination 2009;239(1–3):266–75.
[123] Sarsilmaz C, Yildiz C, Pehlivan D. Drying of apricots in a rotary column cylindrical dryer (RCCD) supported with solar energy. Renew Energy 2000;21(2):117–27.
[124] Togrul IT, Pehlivan D. Mathematical modeling of solar drying of apricots in thin layers. J Food Eng 2002;55(3):209–16.
[125] Amer BMA, Hossain MA, Gottschalk K. Design and performance evaluation of a new hybrid solar dryer for banana. Energy Convers Manage, in press, corrected proof.
[126] Smitabhindu R, Janjai S, Chankong V. Optimization of a solar -assisted drying system for drying bananas. Renew Energy 2008;33(7):1523–31.
[127] Olufayo AA, Ogunkunle OJ. Natural drying of cassava chips in the humid zone of Nigeria. Bioresour Technol 1996;58(1):89–91.
[128] Doymaz I. Sun drying of figs: an experimental study. J Food Eng 2005;71(4):403–7.
[129] Bala BK, Mondol MRA, Biswas BK, Das Chowdury BL, Janjai S. Solar drying of pineapple using solar tunnel drier. Renew Energy 2003;28(2):183–90.
[130] Tarhan S. Selection of chemical and thermal pretreatment combination for plum drying at low and moderate drying air temperatures. J Food Eng 2007;79(1):255–60.
[131] El-Beltagy A, Gamea GR, Amer Essa AH. Solar drying characteristics of strawberry. J Food Eng 2007;78(2):456–64.
[132] Akbulut A, Durmus A. Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer. Energy Article, in press, corrected proof.
[133] Sacilik K, Keskin R, Elicin AK. Mathematical modeling of solar tunnel drying of thin layer organic tomato. J Food Eng 2006;73(3):231–8.
[134] Midilli A, Kucuk H. Mathematical modeling of thin layer drying of pistachio by using solar energy. Energy Convers Manage 2003;44(7):1111–22.
[135] Chen H-H, Hernandez CE, Huang T-C. A study of the drying effect on lemon slices using a closed-type solar dryer. Solar Energy 2005;78(1):97–103.
[136] Lahsasni S, Kouhila M, Mahrouz M, Idlimam A, Jamali A. Thin layer convective solar drying and mathematical modeling of prickly pear peel (*Opuntia ficus indica*). Energy 2004;29(2):211–24.
[137] Jairaj KS, Singh SP, Srikant K. A review of solar dryers developed for grape drying. Solae Energy 2009;83(9):1698–712.
[138] Pangavhane DR, Sawhney RL. Review of research and development work on solar dryers for grape drying. Energy Convers Manage 2002;43(1):45–61.
[139] Fadhel A, Kooli S, Farhat A, Bellghith A. Study of the solar drying of grapes by three different processes. Desalination 2005;185(1–3):535–41.
[140] Barnwal P, Tiwari GN. Grape drying by using hybrid photovoltaic-thermal (PV/T) greenhouse dryer: an experimental study. Solar Energy 2008;82(12):1131–44.
[141] Yaldiz O, Ertekin C, Uzun HI. Mathematical modeling of thin layer solar drying of sultana grapes. Energy 2001;26(5):457–65.
[142] Sharma GP, Verma RC, Pathare P. Mathematical modeling of infrared radiation thin layer drying of onion slices. J Food Eng 2005;71(3):282–6.
[143] Kumar A, Tiwari GN. Effect of mass on convective mass transfer coefficient during open sun and greenhouse drying of onion flakes. J Food Eng 2007;79(4):1337–50.
[144] Sarsavadia PN. Development of a solar -assisted dryer and evaluation of energy requirement for the drying of onion. Renew Energy 2007;32(15):2529–47.
[145] Tripathy PP, Kumar S. Modeling of heat transfer and energy analysis of potato slices and cylinders during solar drying. Appl Therm Eng 2009;29(5–6):884–91.
[146] Tripathy PP, Kumar S. Determination of temperature dependent drying parameters for potato cylinders and slices during solar drying. Energy Convers Manage 2008;49(11):2941–8.
[147] Tripathy PP, Kumar S. Neural network approach for food temperature prediction during solar drying. Int J Therm Sci 2009;48(7):1452–9.

[148] Hatamipour MS, Kazemi HH, Nooralivand A, Nozarpoor A. Drying characteristics of six varieties of sweet potatoes in different dryers. Food Bioprod Process 2007;85(3):171–7.
[149] Bechoff A, Dufour D, Dhuique-Mayer C, Marouze C, Reynes M, Westby A. Effect of hot air, solar and sun drying treatments on provitamin A retention in orange-fleshed sweet potato. J Food Eng 2009;92(2):164–71.
[150] Diamante LM, Munro PA. Mathematical modeling of the thin layer solar drying of sweet potato slices. Solar Energy 1993;51(4):271–6.
[151] Jain D, Tiwari GN. Thermal aspects of open sun drying of various crops. Energy 2003;28(1):37–54.
[152] El-Sabaii AA, Aboul-Enein S, Ramadan MRI, El-Gohary HG. Empirical correlations for drying kinetics of some fruits and vegetables. Energy 2002;27(9):845–59.
[153] Jain D, Tiwari GN. Effect of greenhouse on crop drying under natural and forced convection I: evaluation of convective mass transfer coefficient. Energy Convers Manage 2004;45(5):765–83.
[154] Jain D, Tiwari GN. Effect of greenhouse on crop drying under natural and forced convection II. Thermal modeling and experimental validation. Energy Convers Manage 2004;45(17):2777–93.
[155] Sacilik K. Effect of drying methods on thin-layer drying characteristics of hull-less seed pumpkin (*Cucurbita pepo* L.). J Food Eng 2007;79(1): 23–30.
[156] Kadam DM, Samuel DVK. Convective flat-plate solar heat collector for cauliflower drying. Biosyst Eng 2006;93(2):189–98.
[157] Ayensu A. Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy 1997;59(4–6):121–6.
[158] Hossain MA, Woods JL, Bala BK. Optimisation of solar tunnel drier for drying of chilli without color loss. Renew Energy 2005;30(5):729–42.
[159] Hossain MA, Bala BK. Drying of hot chilli using solar tunnel dryer. Solar Energy 2007;81(1):85–92.
[160] Chauhan PM, Choudhury C, Garg HP. Comparative performance of coriander dryer coupled to solar air heater and solar air-heater-cum-rock bed storage. Appl Therm Eng 1996;16(6):475–86.
[161] Prasad J, Vijay VK, Tiwari GN, Sorayan VPS. Study on performance evaluation of hybrid drier for turmeric (*Curcuma longa* L.) drying at village scale. J Food Eng 2006;75(4):497–502.
[162] Kooli S, Fadhel A, Farhat A, Belghith A. Drying of red pepper in open sun and greenhouse conditions: Mathematical modeling and experimental validation. J Food Eng 2007;79(3):1094–103.
[163] Akpinar EK, Bicer Y. Mathematical modeling of thin layer drying process of long green pepper in solar dryer and under open sun. Energy Convers Manage 2008;49(6):1367–75.
[164] McDoom IA, Ramsaroop R, Saunders R, Kai TA. Optimization of solar crop drying. Renew Energy 1999;16(1–4):749–52.
[165] Phillips AL. Drying coffee with solar-heated air. Solar Energy 1965;9(4):213–6.
[166] Patil BG, Ward GT. Simulation of solar air drying of rapeseed. Solar Energy 1989;43(5):305–20.
[167] Muller J, Reisinger G, Kisgeci J, Kotta E, Tesic M, Muhlbauer W. Development of a greenhouse-type solar dryer for medicinal plants and herbs. Solar Wind Technol 1989;6(5):523–30.
[168] Janjai S, Tung P. Performance of a solar dryer using hot air from roof-integrated solar collectors for drying herbs and spices. Renew Energy 2005;30(14):2085–95.
[169] Janjai S, Srisittipokakun N, Bala BK. Experimental and modeling performances of a roof-integrated solar drying system for drying herbs and spices. Energy 2008;33(1):91–103.
[170] Arslan D, Ozcan MM. Evaluation of drying methods with respect to drying kinetics, mineral content and color characteristics of rosemary leaves. Energy Convers Manage 2008;49(5):1258–64.
[171] Kumar A, Tiwari GN. Thermal modeling of a natural convection greenhouse drying system for jaggery: an experimental validation. Solar Energy 2006;80(9):1135–44.
[172] Bahnasawy AH, Shenana ME. A mathematical model of direct sun and solar drying of some fermented dairy products (Kishk). J Food Eng 2004;61(3):309–19.
[173] Nijmeh MN, Ragab AS, Emeish MS, Jubran BA. Design and testing of solar dryers for processing food wastes. Appl Therm Eng 1998;18(12):1337–46.
[174] Banout J, Ehl P, Havlik J, Lojka B, Polesny Z, Verner V. Design and performance evaluation of a double-pass solar drier for drying of red chilli (*Capsicum annum* L.). Solar Energy 2011;85:506–15.
[175] Maiti S, Patel P, Vyas K, Eswaran K, Ghosh PK. Performance evaluation of a small scale indirect solar dryer with static reflectors during non-summer months in the Saurashtra region of western India. Solar Energy 2011;85:2686–96.
[176] Fadhel MI, Sopian K, Daud WRW, Alghoul MA. Review on advanced of solar assisted chemical heat pump dryer for agriculture produce. Renew Sustain Energy Rev 2011;15:1152–68.